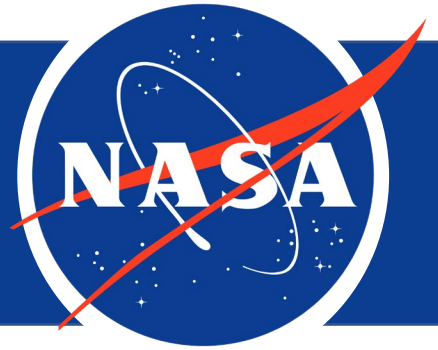
Phase Change Materials for Photonics in NASA Science and Space Missions



Hyun Jung Kim

Research Physicist at NASA Langley Research Center

April 12th, 2023
(MSE colloquium at U. of Maryland)

NASA's Langley Research Center

HAMPTON, VIRGINIA

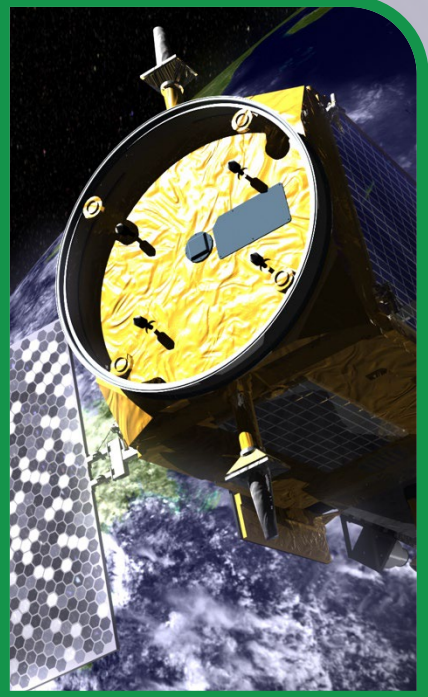
National Aeronautics and Space Administration

NASA Organization Structure

National Aeronautics and Space Administration

Langley Research Center

SCIENCE



Studying Earth and worlds beyond

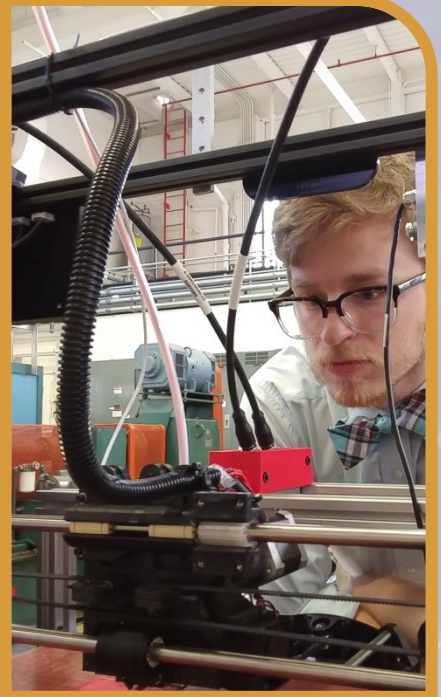
SPACE EXPLORATION

Tools to take us from Moon to Mars

AERONAUTICS

Cleaner, faster, safer air transport

TRANSFORMATION

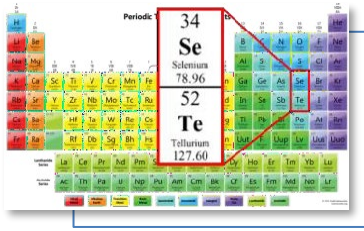


Future of Langley's work and workforce

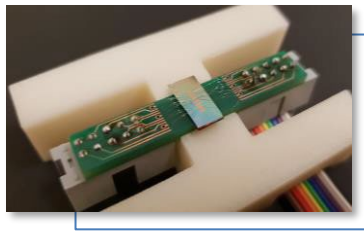
STEM ENGAGEMENT

A new generation of explorers

Outline



Phase change material (PCM) & P-ACTIVE



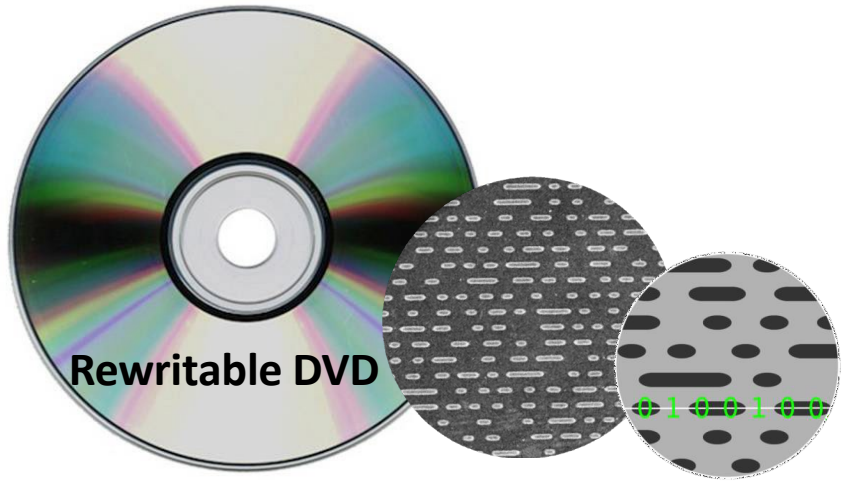
Electrical switching of PCM metasurfaces

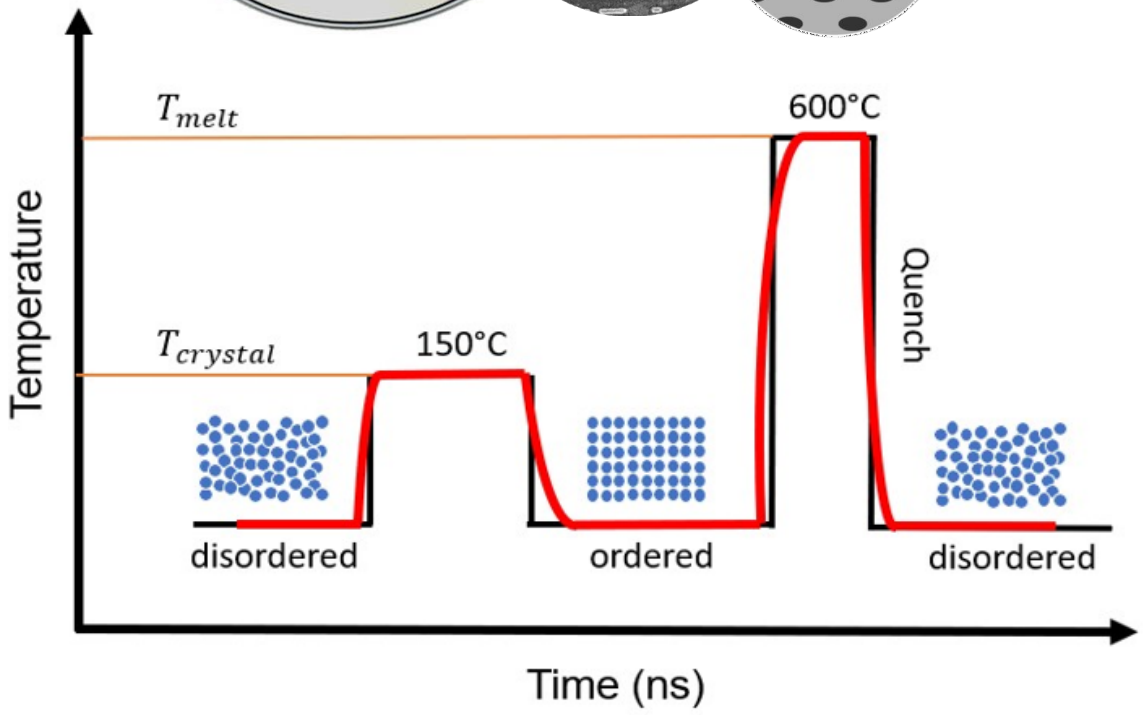
Path forward to Space

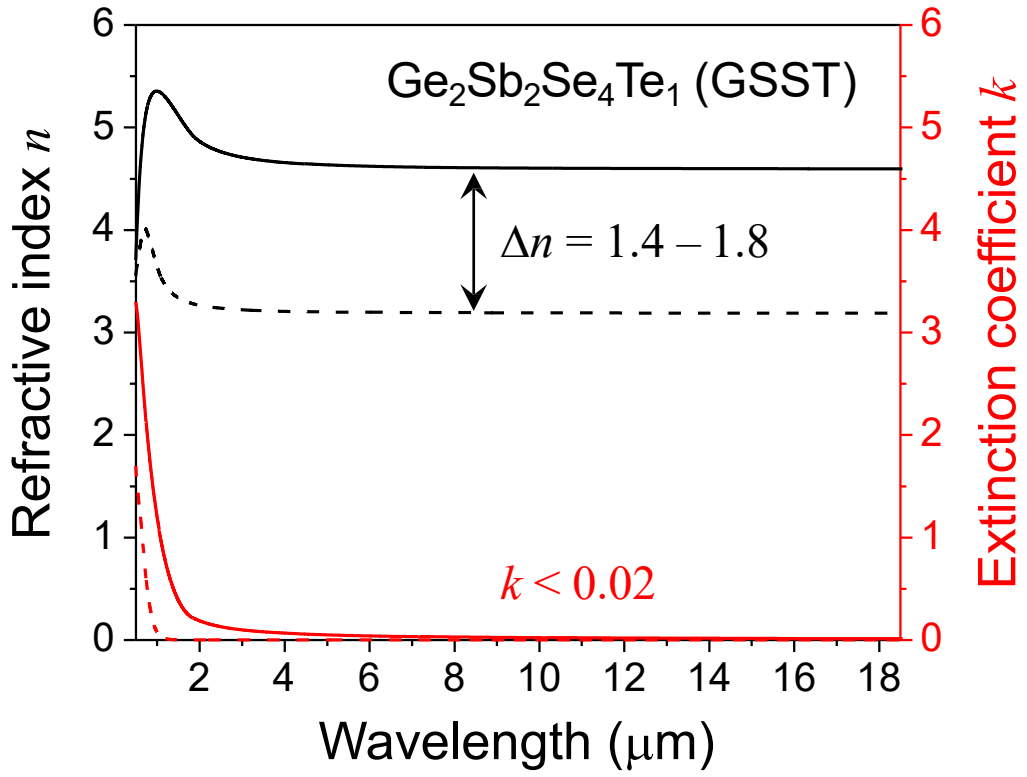
How can I work for or with NASA

What is the Phase Change Materials for Photonics

Phase change materials has long history (since 1966)





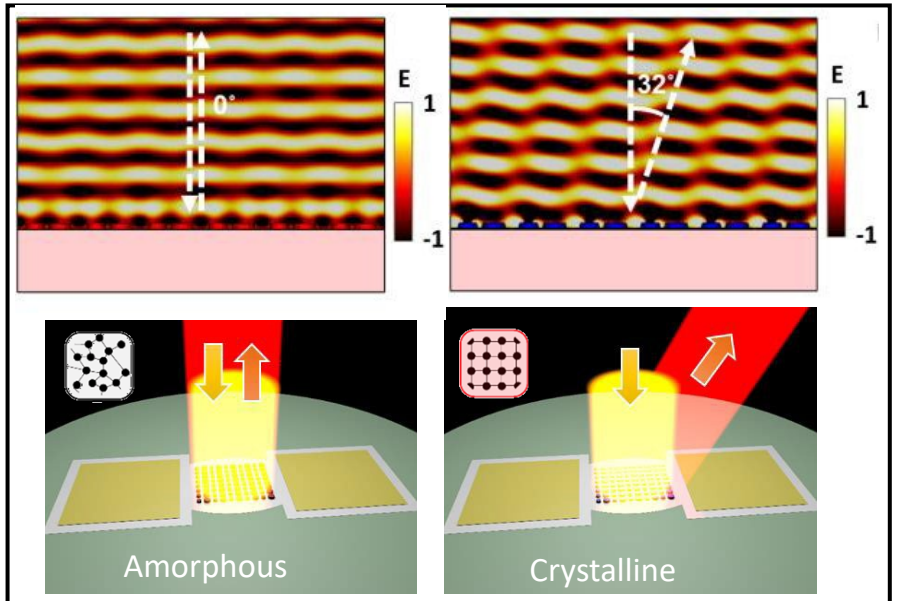


✓ Index change: Δn = 1.4 – 1.8

✓ Loss: k < 0.02

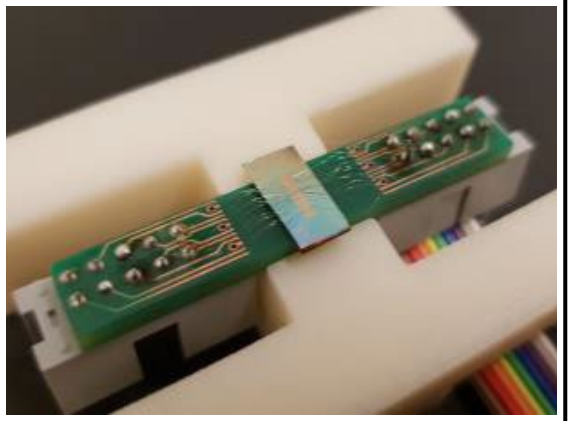
Opt. Lett. **43**, 94 (2018);
Nat. Commun. **10**, 4279 (2019);
J. Of Physics: Photonics **3.2** (2021) 024008

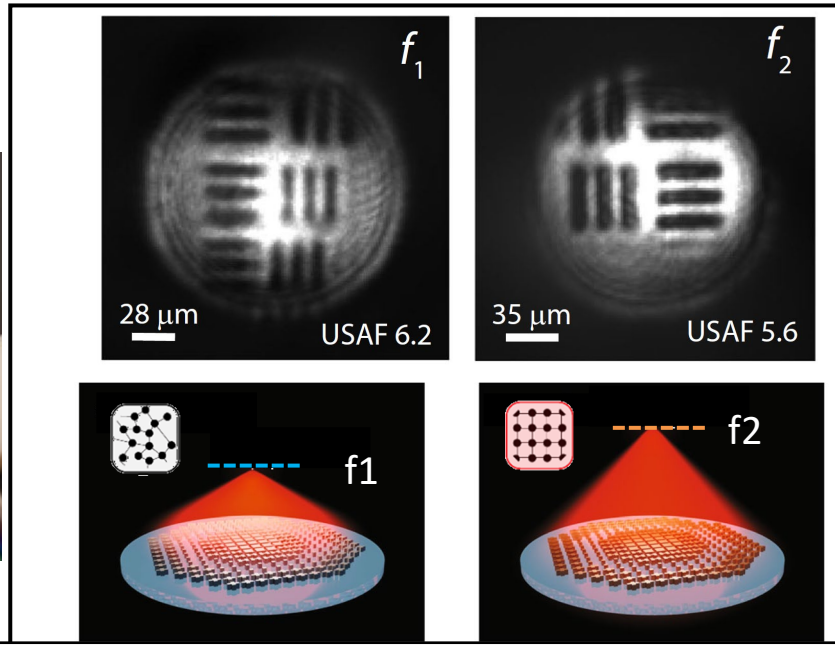
Reconfigurable Metasurface Optics using PCM



Nature Nano. 16(6), 1-6 (2021)

Packaged PROWESS

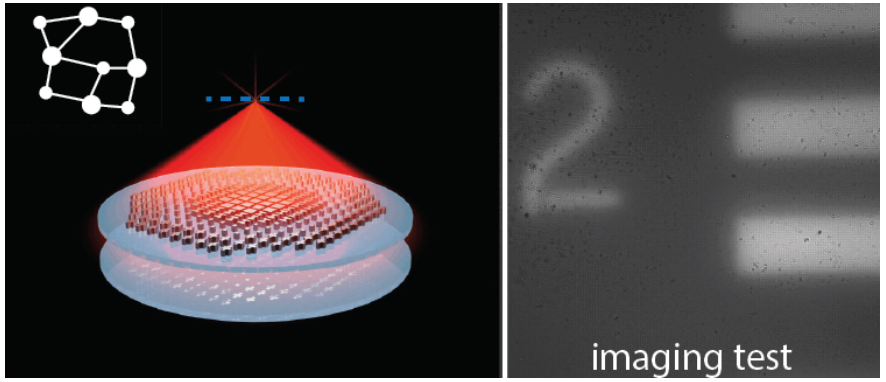




A parfocal zoom lens without moving parts

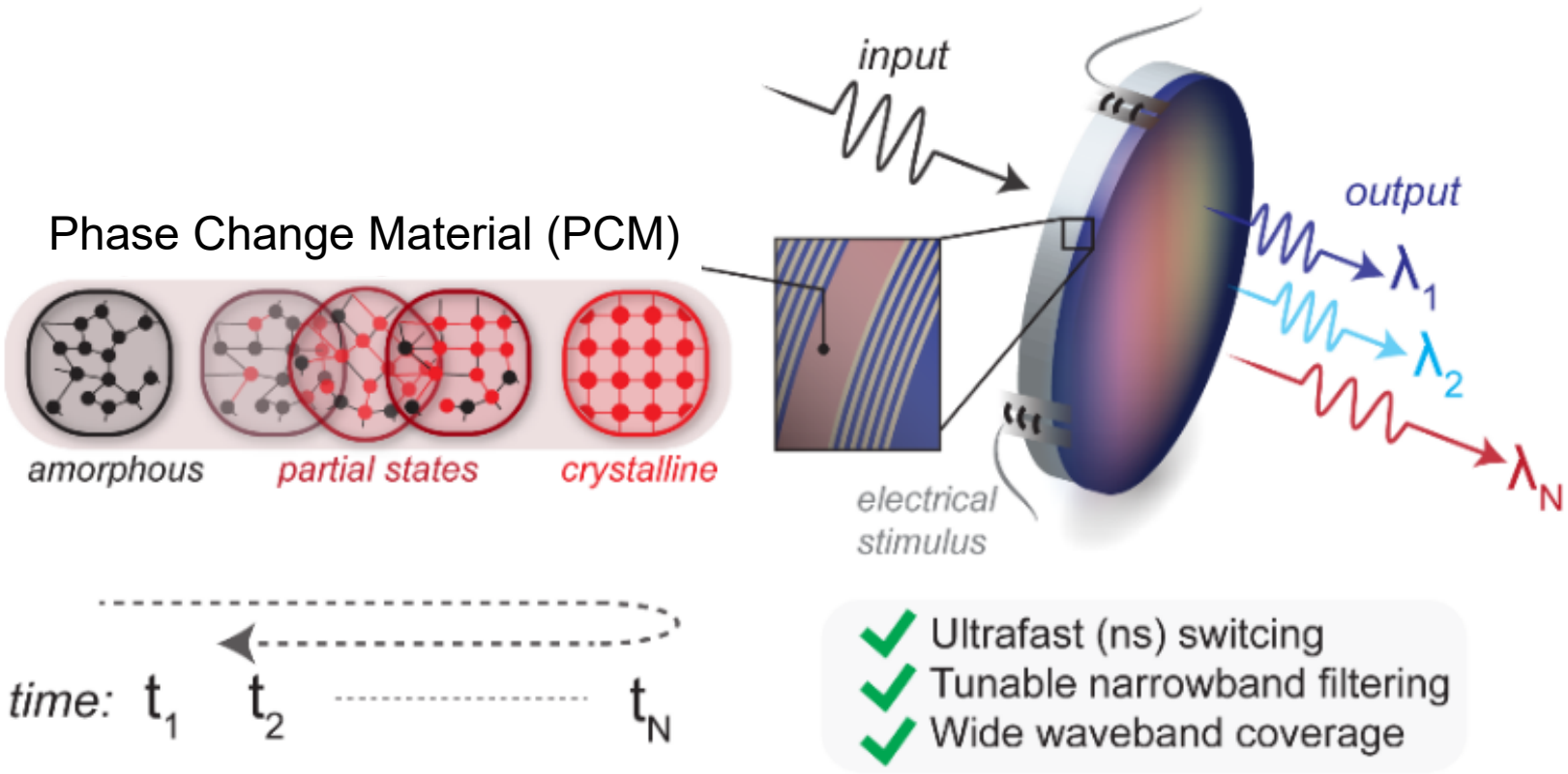
10x optical zoom

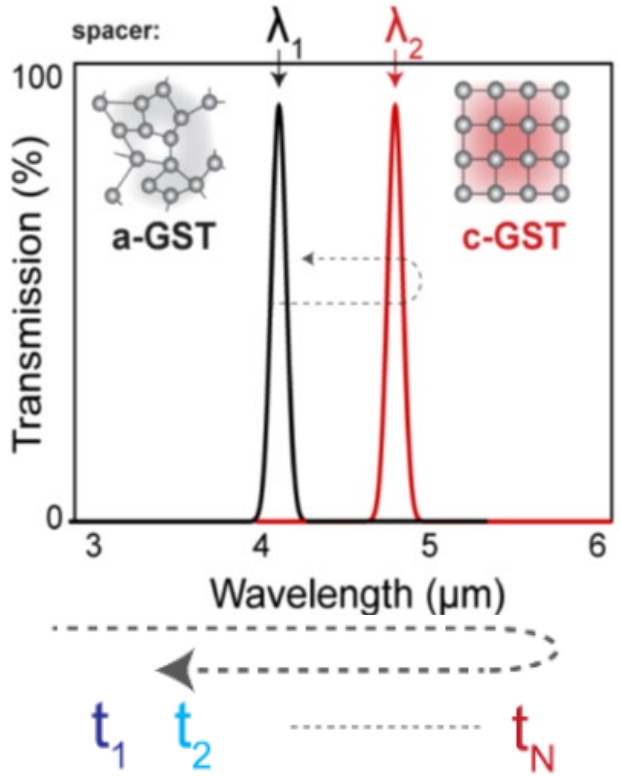
***Adv. Opt. Mater.* 10, 2200721 (2022)**



Exploiting the extraordinary refractive index contract in PCMs has opened the door to unprecedented functionalities in photonic components

PCM-based Actively Tunable Filter (P-ACTIVE)

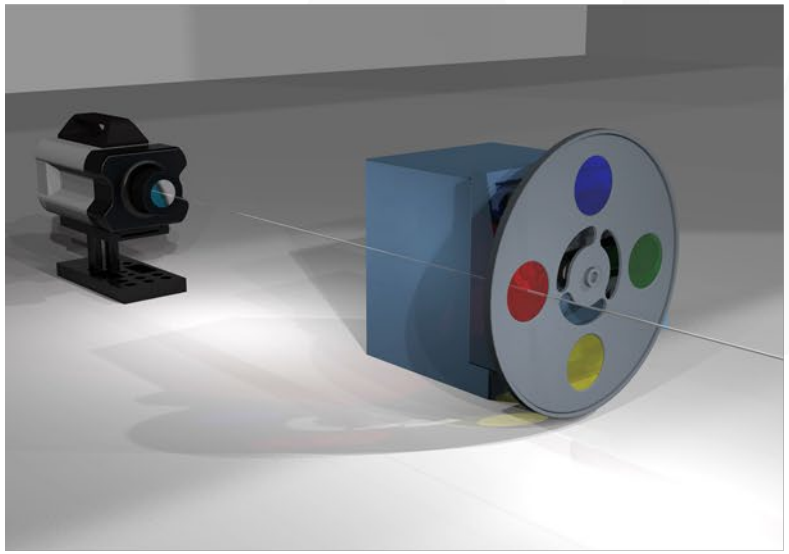




P-ACTIVE

State of the Art:

- ✓ Filter wheels comprised of several static filters physically rotate to switch spectral passband
- ✓ Has moving parts, large mass, slow response time (ms), and provides limited spectral resolution
- ✓ 800g (weight), 725cm^3 (volume), 15W to power motor



P-ACTIVE:

- ✓ Increased spectral and temporal resolutions
  - ✓ GHz (ns) switching speed (10^6x improvement!)
  - ✓ Continuously-tunable passband
- ✓ Single-component, non-volatile, broad tunability
- ✓ 10g (weight), 0.253cm^3 (volume), ~mW average power to tune filter

P-ACTIVE can offer a flexible platform that can meet arbitrary mission requirements and provide more science information

NASA Earth Missions

On-orbit Missions and Partnerships

- International
- Interagency
- Primary Ops
- Extended Ops

SMAP
2014

DSCOVR
(NOAA)
2015

GRACE-FO
2018

CYGNSS
(EVM-1)
2016

ICESat-2
2018

International Space Station

- LIS on ISS 2017
- SAGE III on ISS 2017
- TSIS-1 on ISS 2017
- ECOSTRESS on ISS (EVI-2) 2018
- GEDI on ISS (EVI-2) 2018
- OCO-3 on ISS 2019

OCO-2
2014

Suomi NPP
(NOAA)
2011

Landsat 8
(USGS)
2013

SORCE
2003

Aqua
2002

SAGE
(Stratospheric Aerosol and Gas Experiment)

GPM
Core Observatory
2014

Terra
1999

Aura
2004

CALIPSO
2006

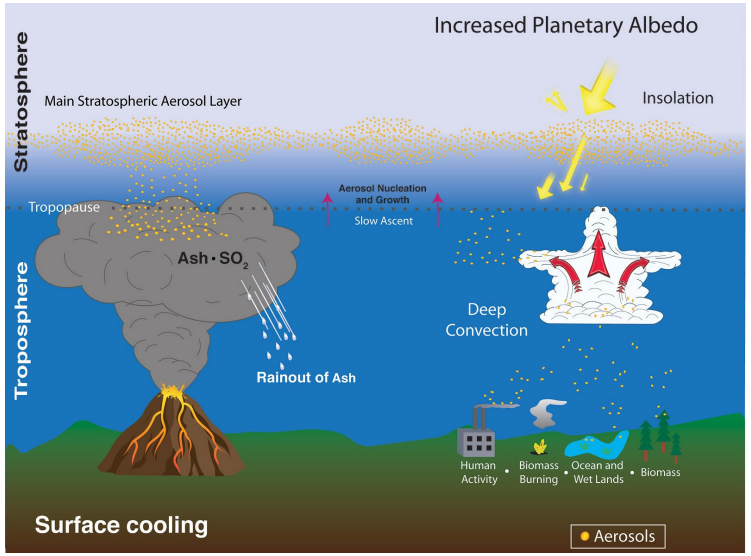
CloudSat
2006

Landsat 7
(USGS)
1999

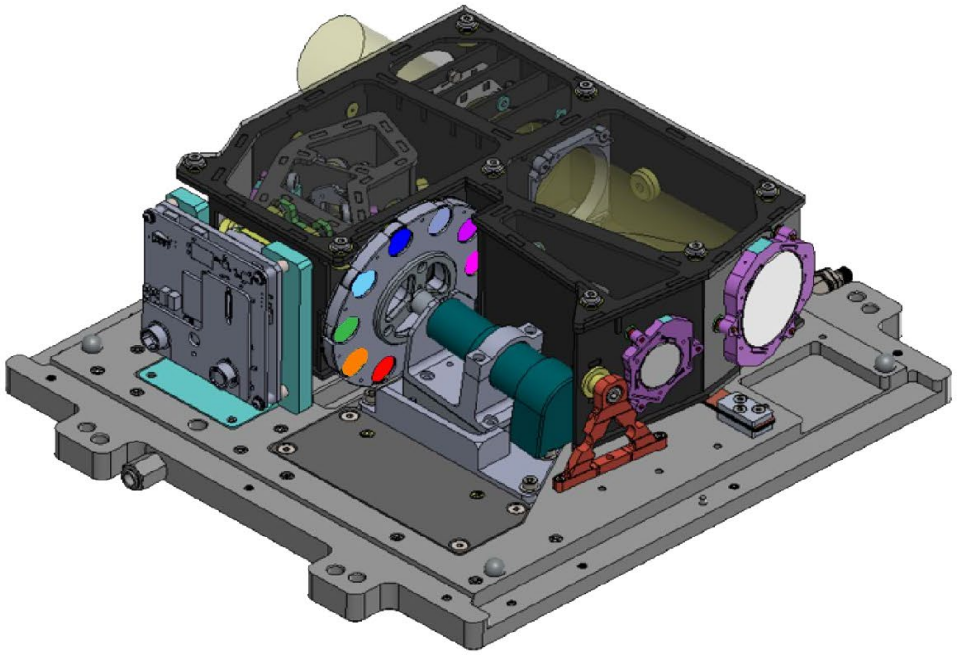
OSTM/Jason 2
(NOAA)
2008

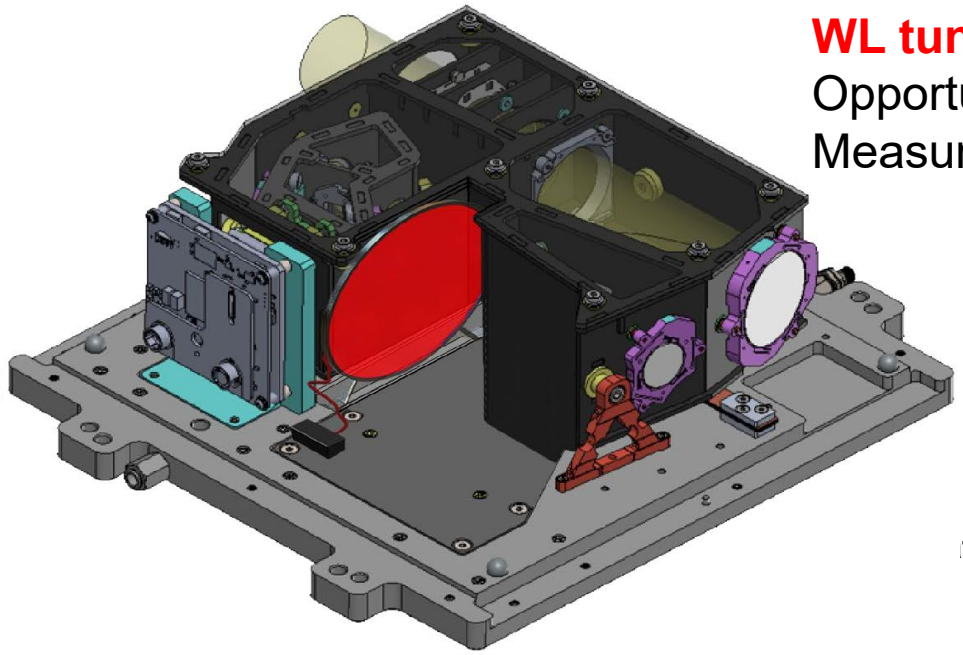
NASA SAGE mission

https://www.nasa.gov/sage3-iss



I. SAGE precisely measuring the constituents that influence the balance of our atmosphere
II. SAGE-IV was developed at 1/10th the cost of SAGE-III
III. 6U Cubesats and Smallsats open opportunities for Rideshare launches
IV. **SWaP + No moving part + More WL tunability** = More Opportunity = More Measurements



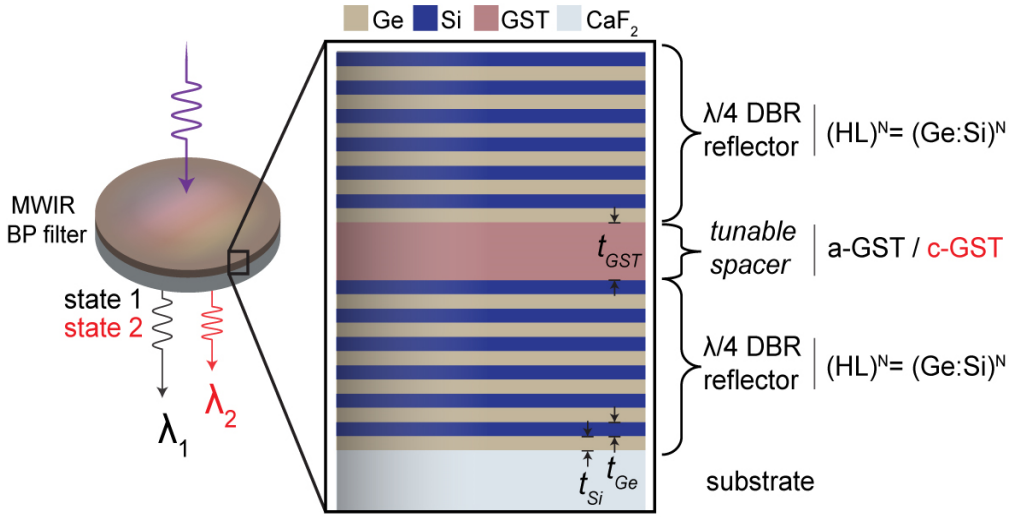


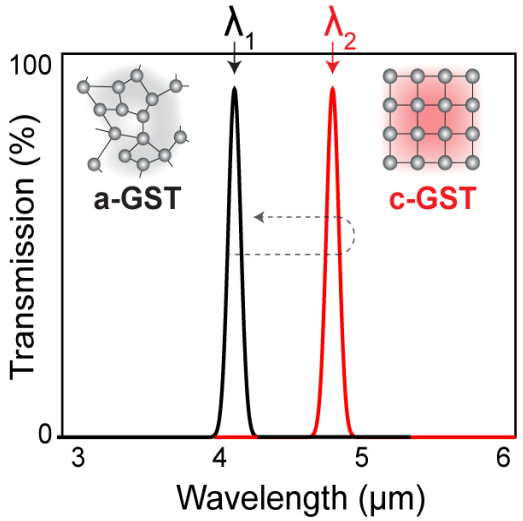
tional Aeronautics and Space Administration

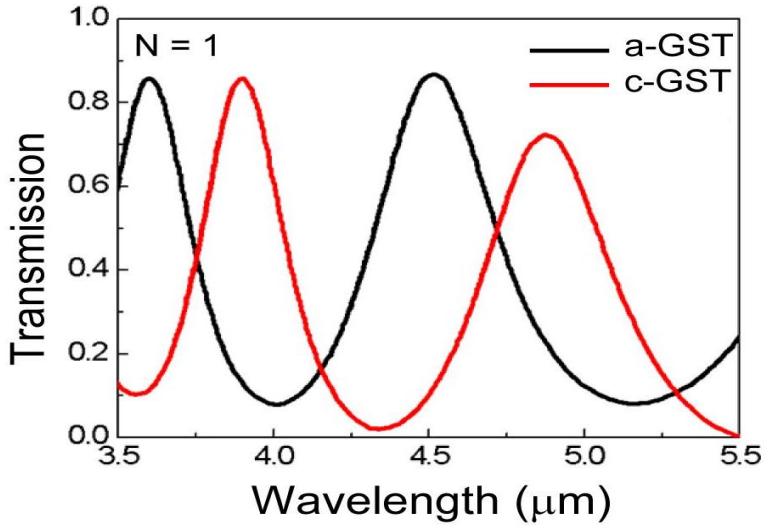
NASA

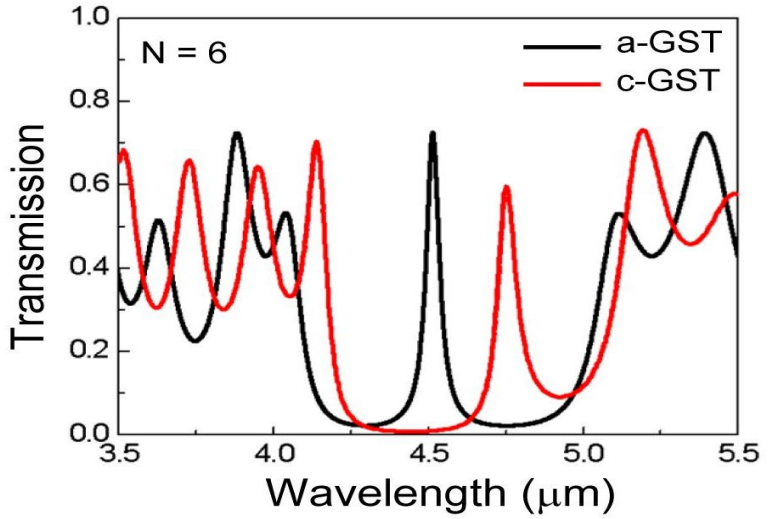
Prototype 1: Fabry-Perot Bandpass Filter with $Ge_2Sb_2Te_5$ cavity

center wavelength (λ_1 or λ_2) shift depending GST crystallinity (refractive index)



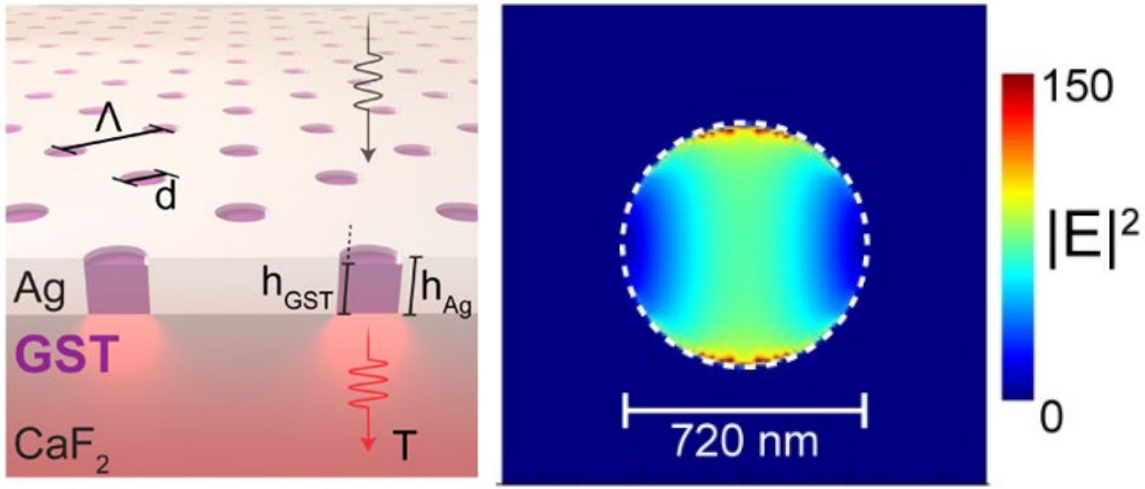


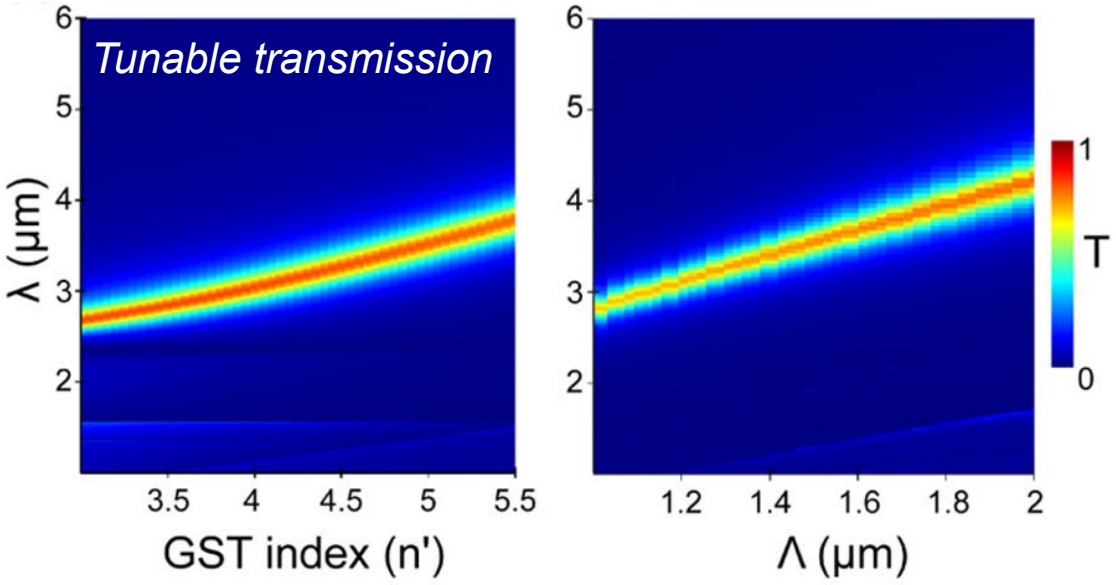




C. Williams. et al, Optics Express 28(7), 10583, 2020

Prototype 2: Metasurface filter with embedded GST

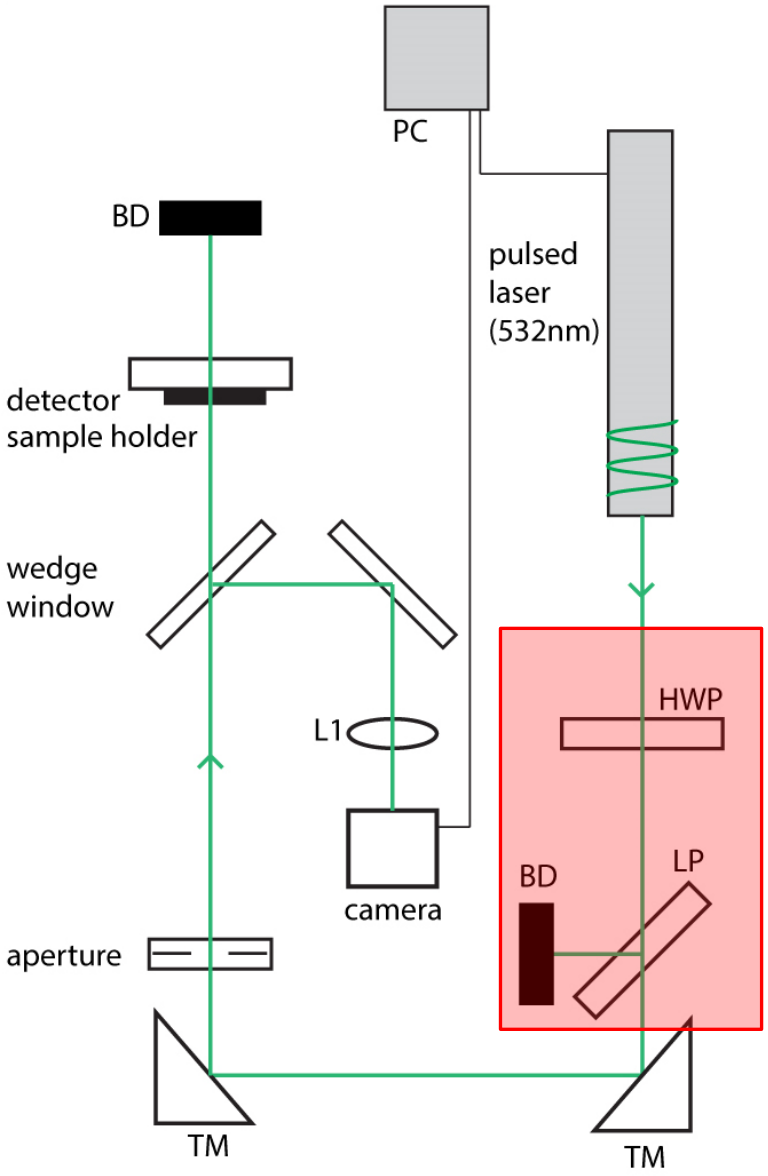


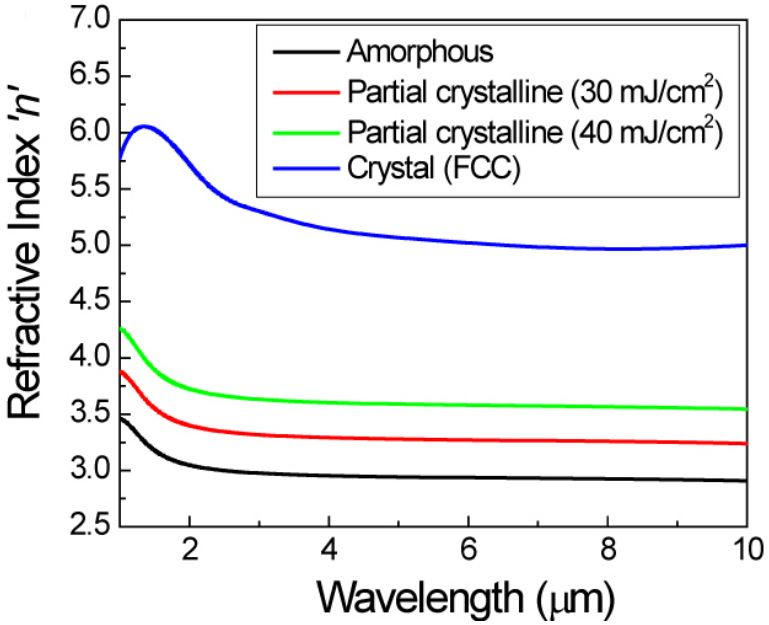


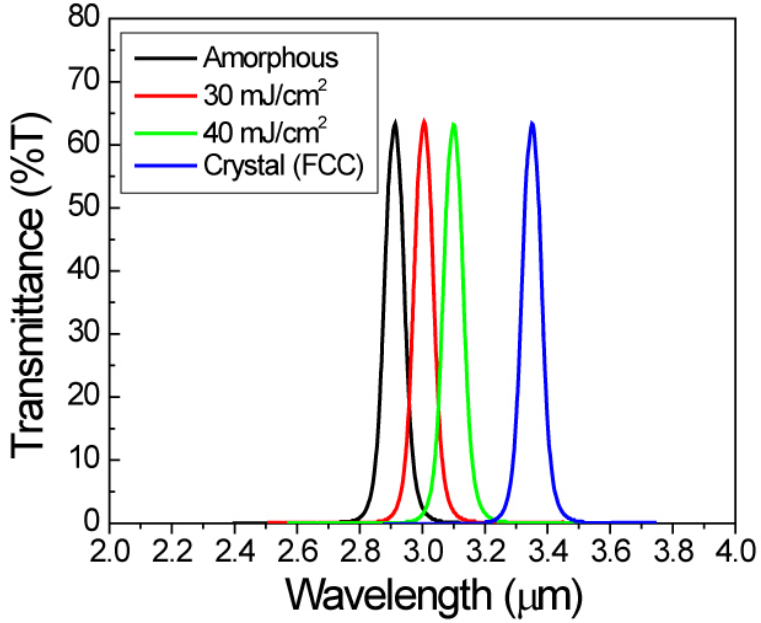
- Metasurfaces are sub-wavelength arrays which can be designed to strongly interact with the light
- We utilized a Plasmonic Nanohole Array (PNA) metasurface filter
- Integration of $Ge_2Sb_2Te_5$ (GST) with PNA
- Transmission response dependent on hole index. Holes filled with GST (tunable)
- **GST filled nanohole arrays associated resonance at particular WL in metal film**
  → transmission mode filtering

M. Julian et al., Optica, 7(7), 746-754, 2020

Pulsed-laser switching setup enables rapid center wavelength tuning

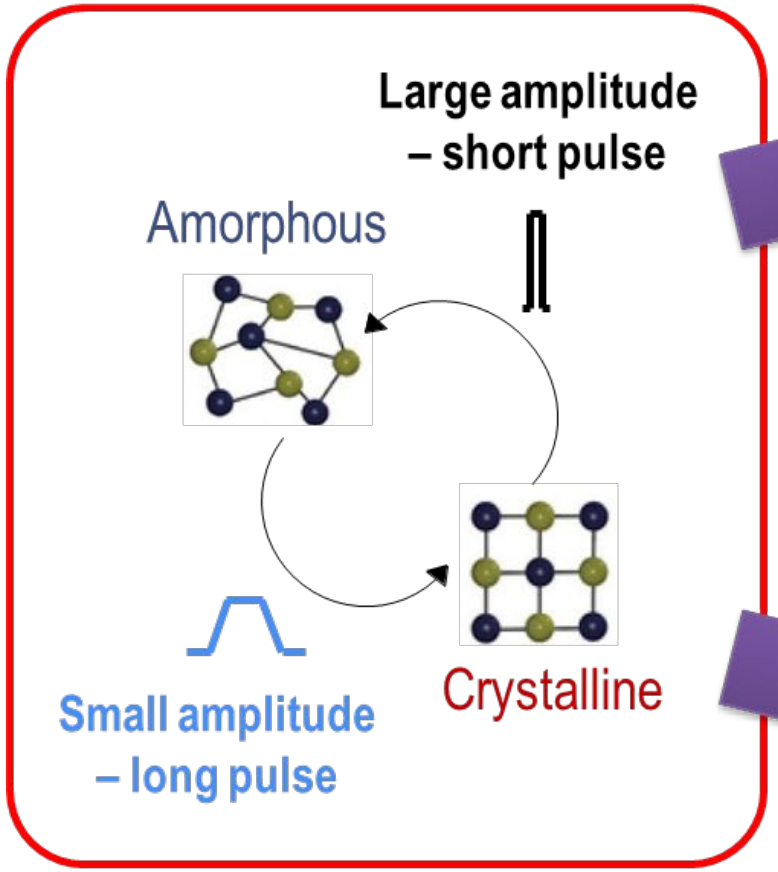


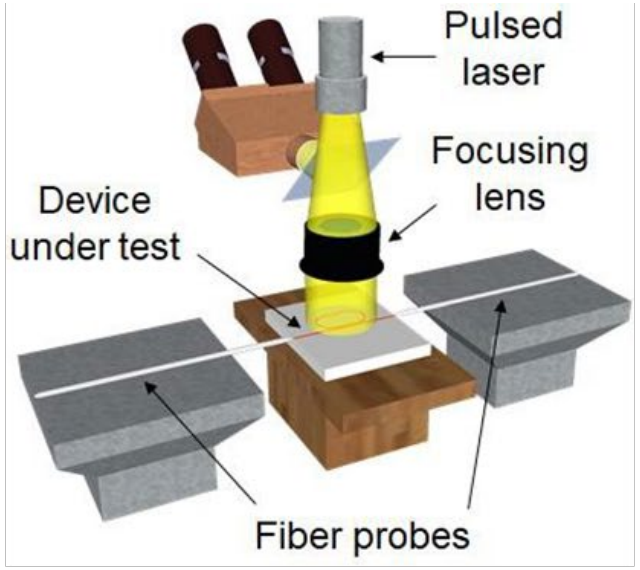




- GST-PCM is generally considered to be a 2-bit material (‘0’ / ‘1’), either amorphous (2.9μm) or crystalline state (3.4μm).
- Partial crystallizations of GST-PCM experimental demonstrations

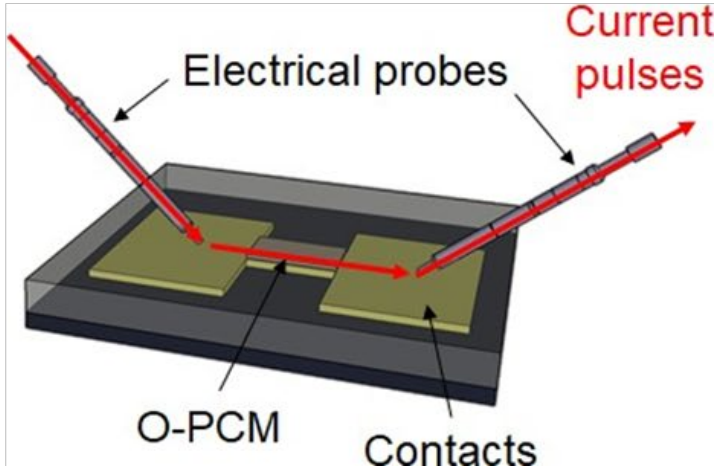
Optical and electrical switching of PCMs





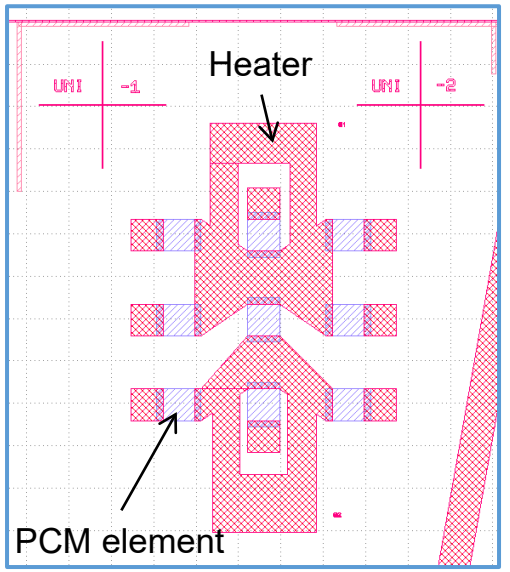
Optical (laser) switching

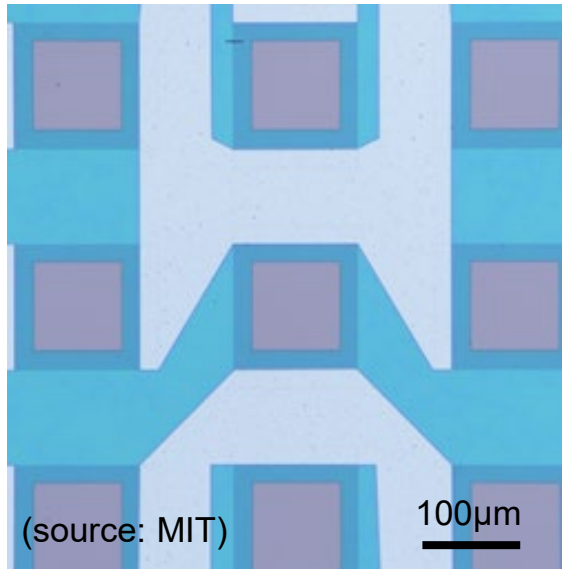
Electro-thermal switching

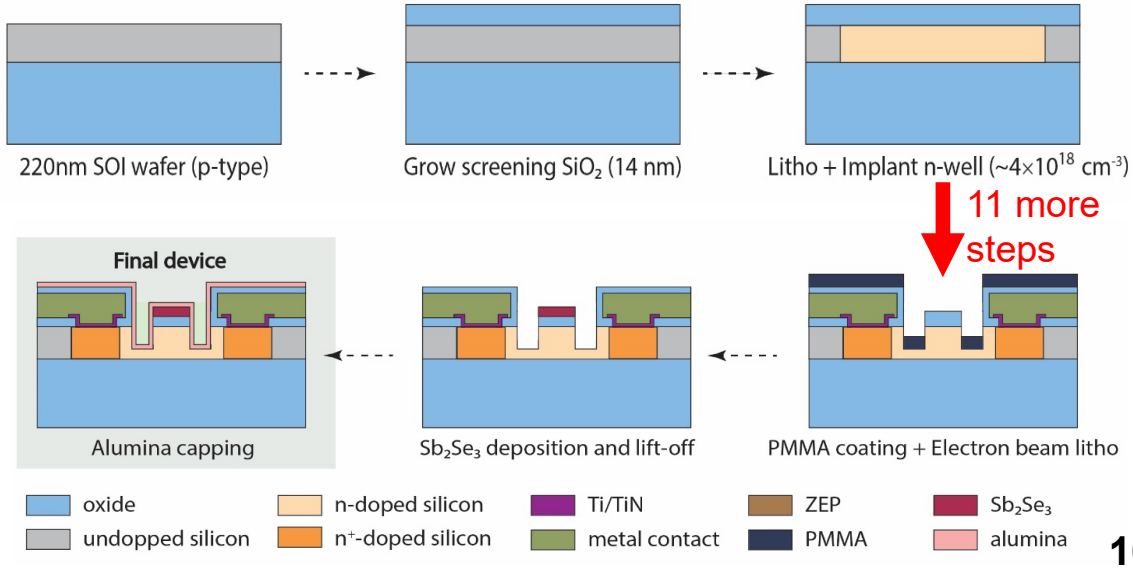


Electrode Heater Array is the core of the technology

- A universal reconfigurable meta-optics/photonics array integrating phase change materials (PCM)
- Programmable 2-D high-density matrix for element-level arbitrary optical property manipulation
- Array of elements containing silicon heaters with PCMs and integrated diode selectors and cross-bar electrical connections
- Scalable, CMOS-compatible manufacturing

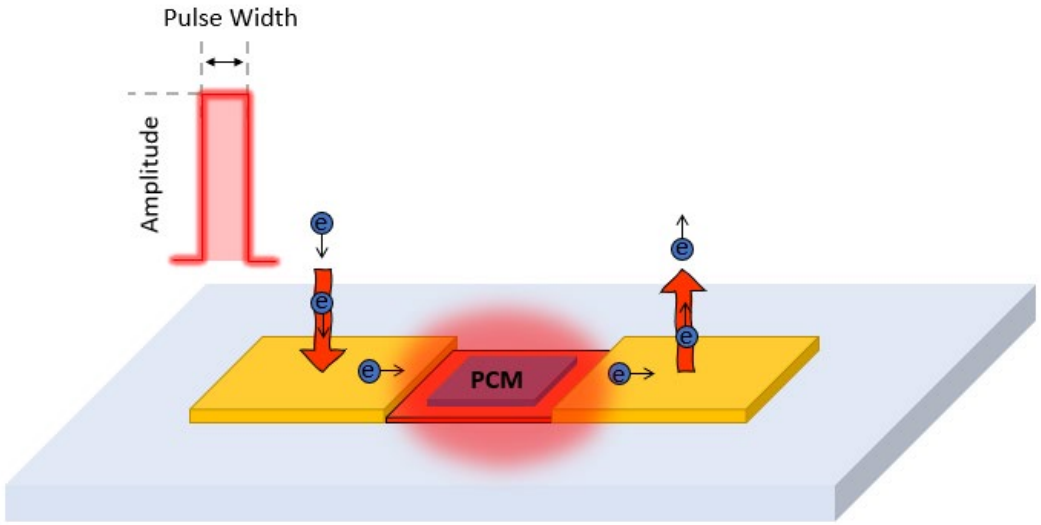


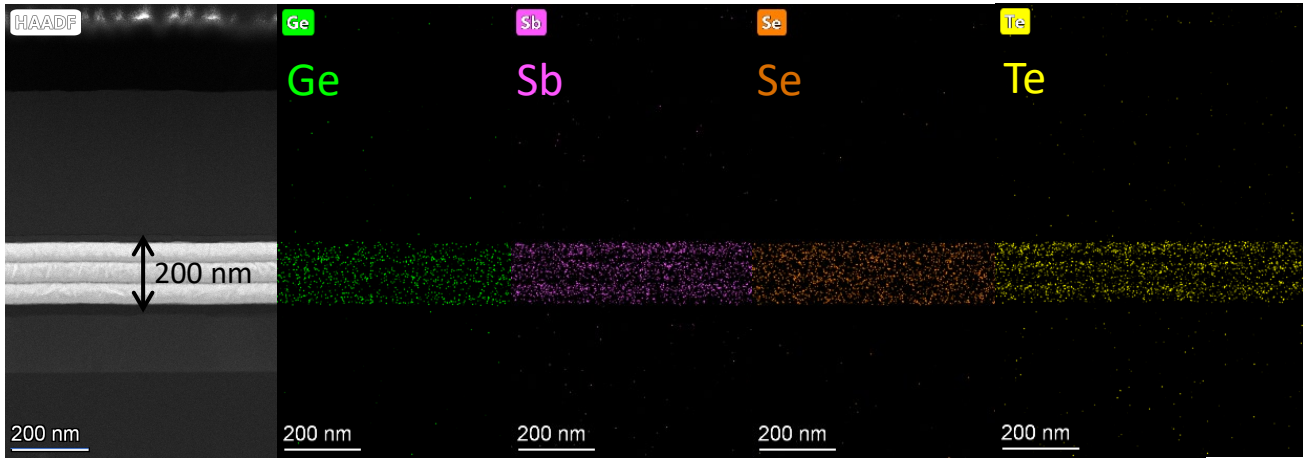




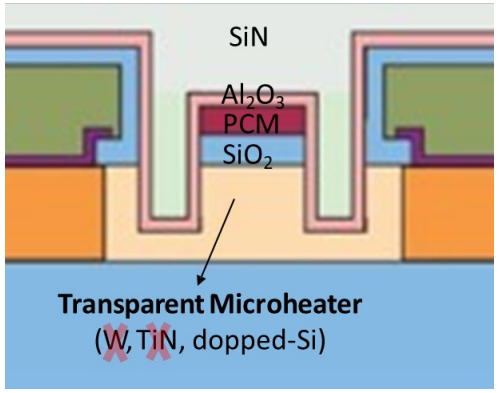
C. Popescu. et al, SPIE Proc. https://doi.org/10.1117/12.2657208 (2023)

Switching PCM via electrical pulses



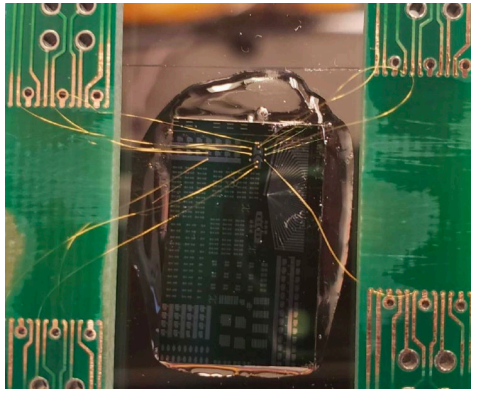


Device Architecture



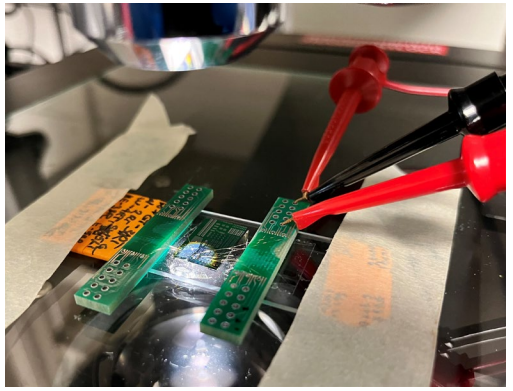
Electrode design change and different encapsulation employed

Fabrication



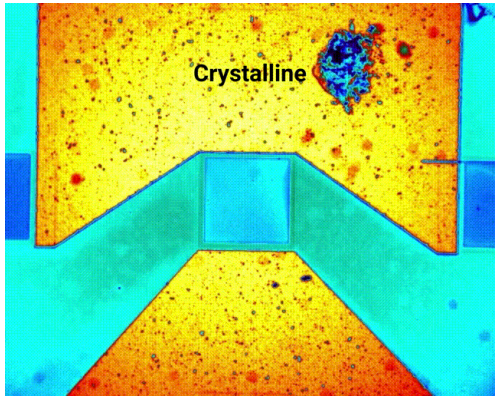
Prototype with (transparent) electrode heater

Measurement



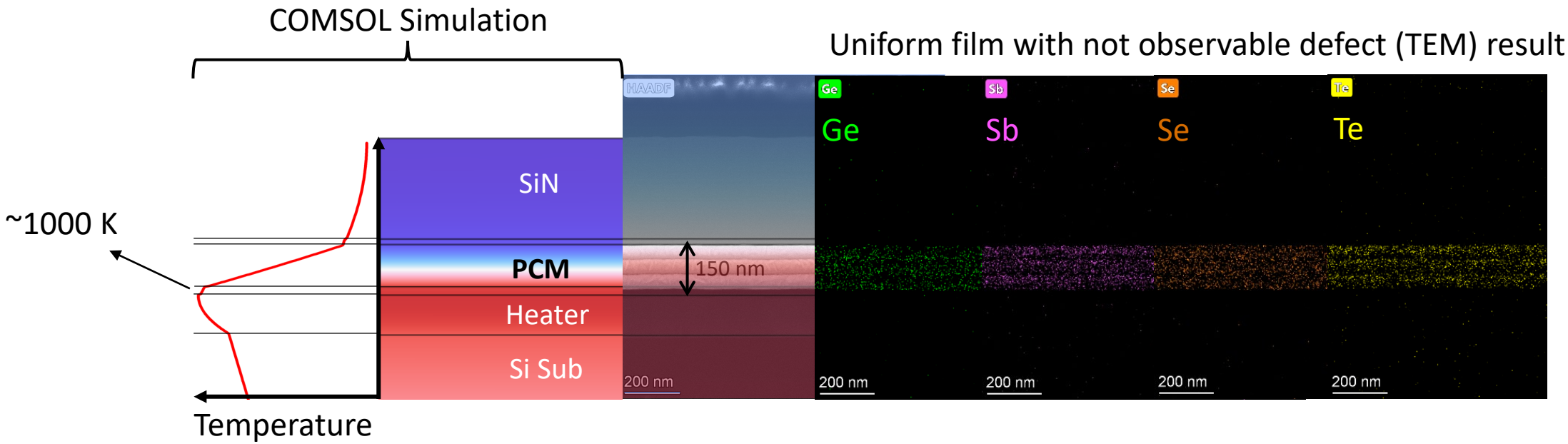
Polished sample for transmittance testing

Evaluation

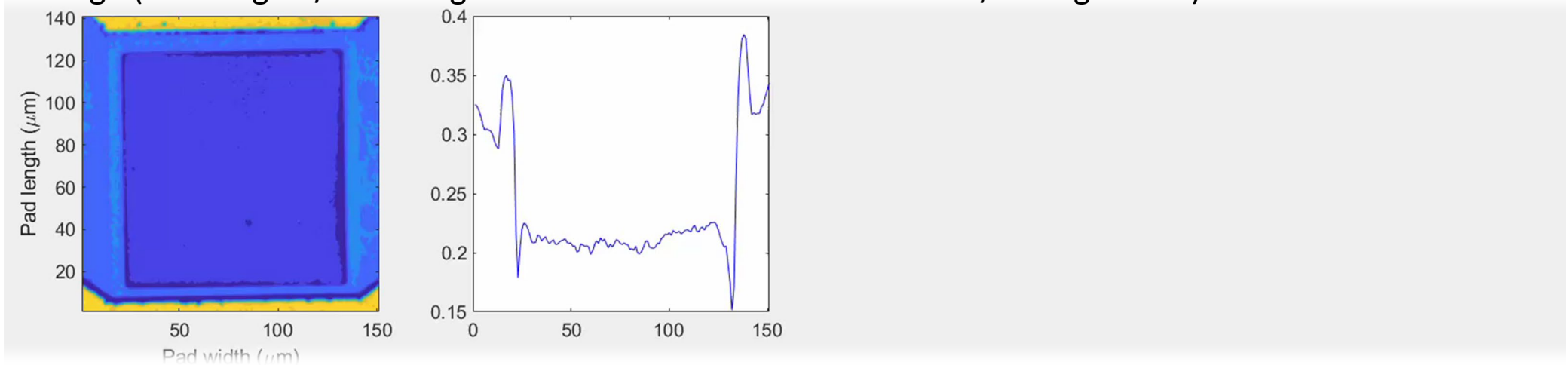


> 35,000 switching cycles demonstrated

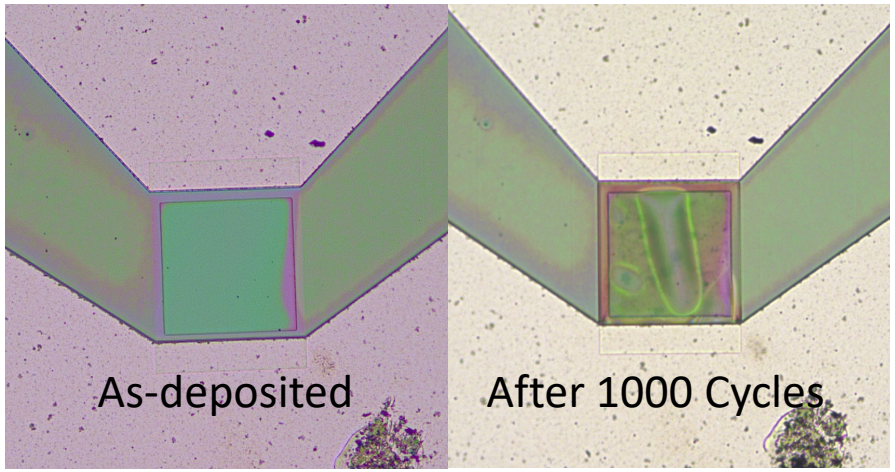
Durability and source of failure (periodically sent A and C pulses)



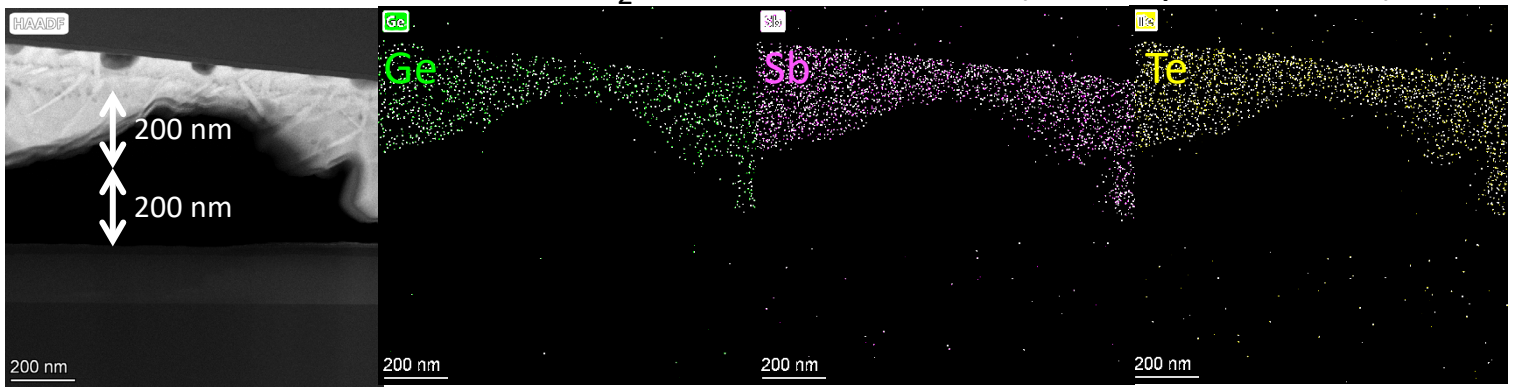
IR image (unchanged / near edge area as well as delaminated area / change color)

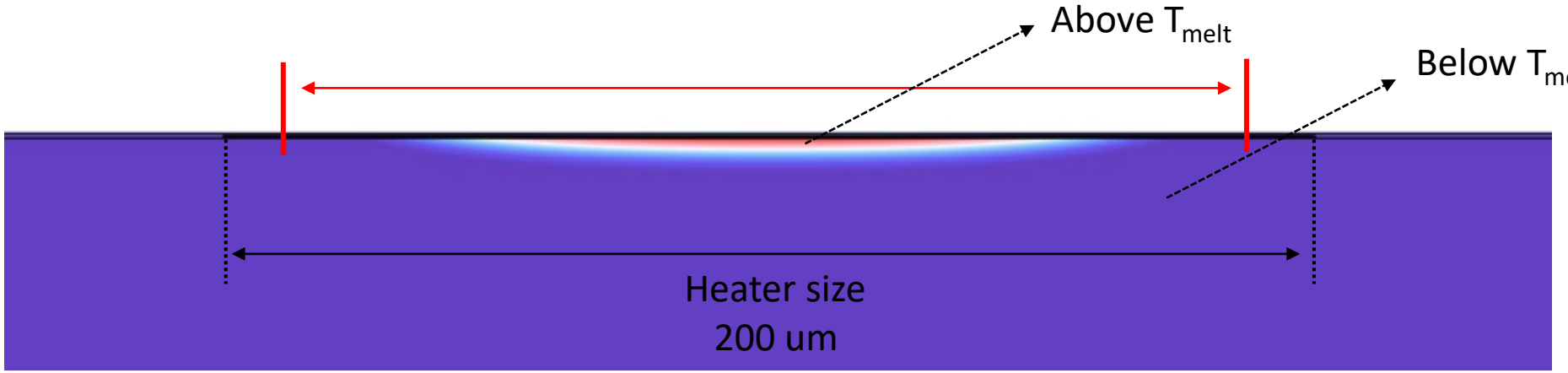


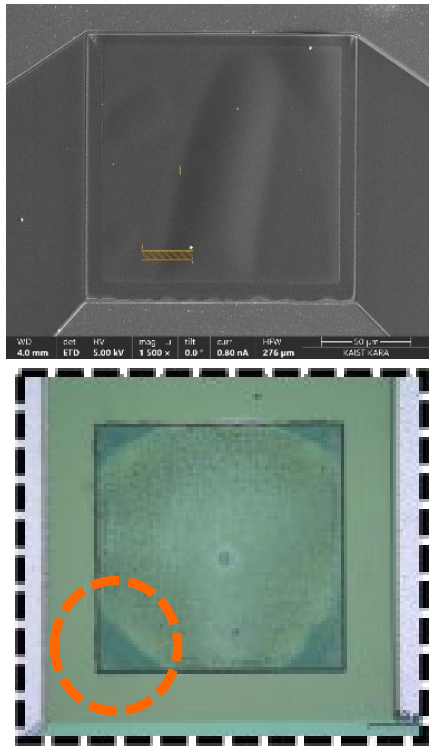
Durability and source of failure



Delamination between SiO_2 and PCM interface (max. up to 1000 K)



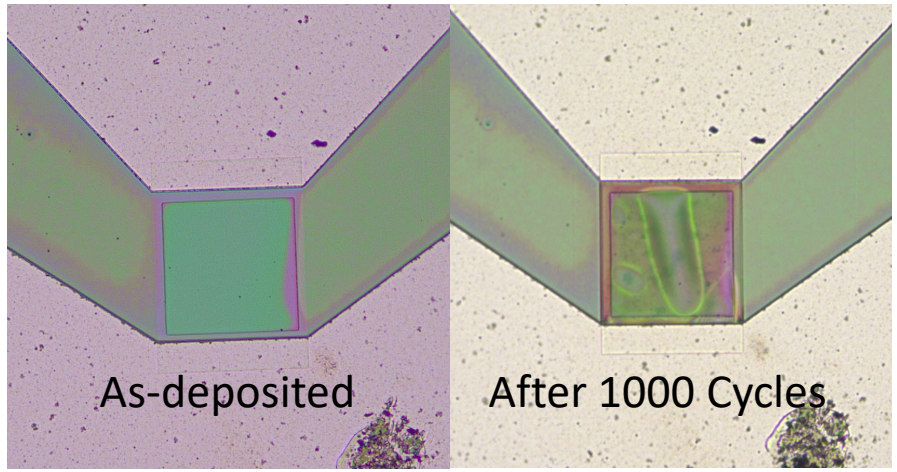


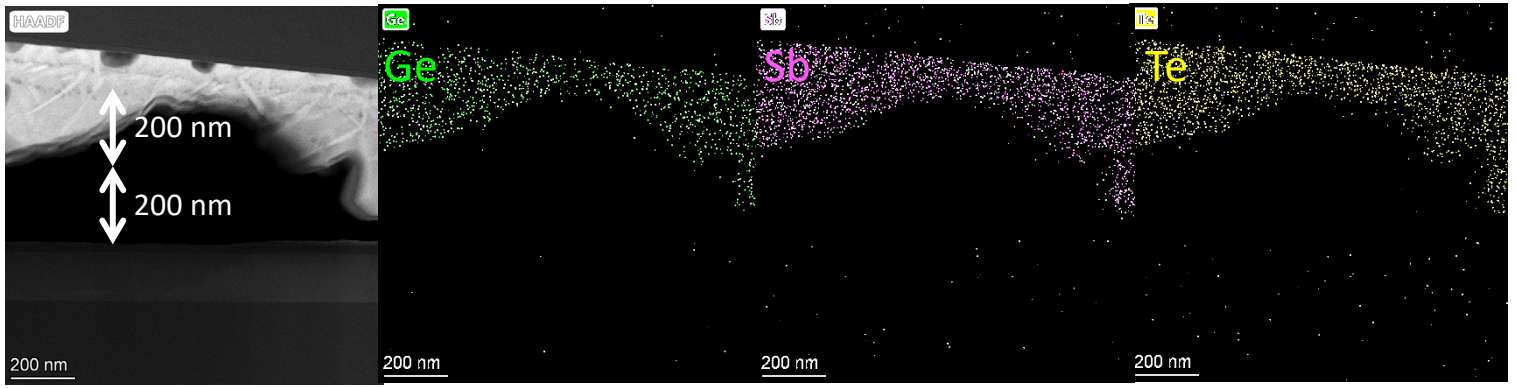


Three major reasons…and more!

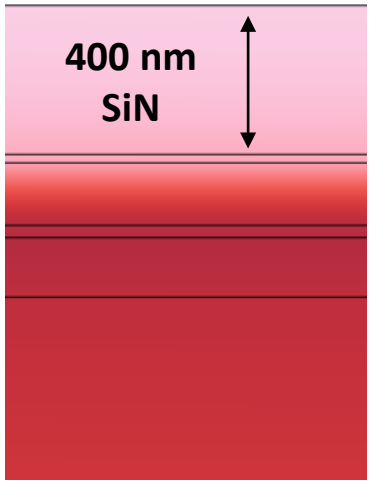
- PCM is not bonded well to the SiO_2 layer
- Non-uniform stoichiometry of GSST (Ge-rich area closer to the heater side), uniformity on crystallinity
- Lateral heat distribution profile (COMSOL simulation), sharp temperature gradient near the edges of the heater

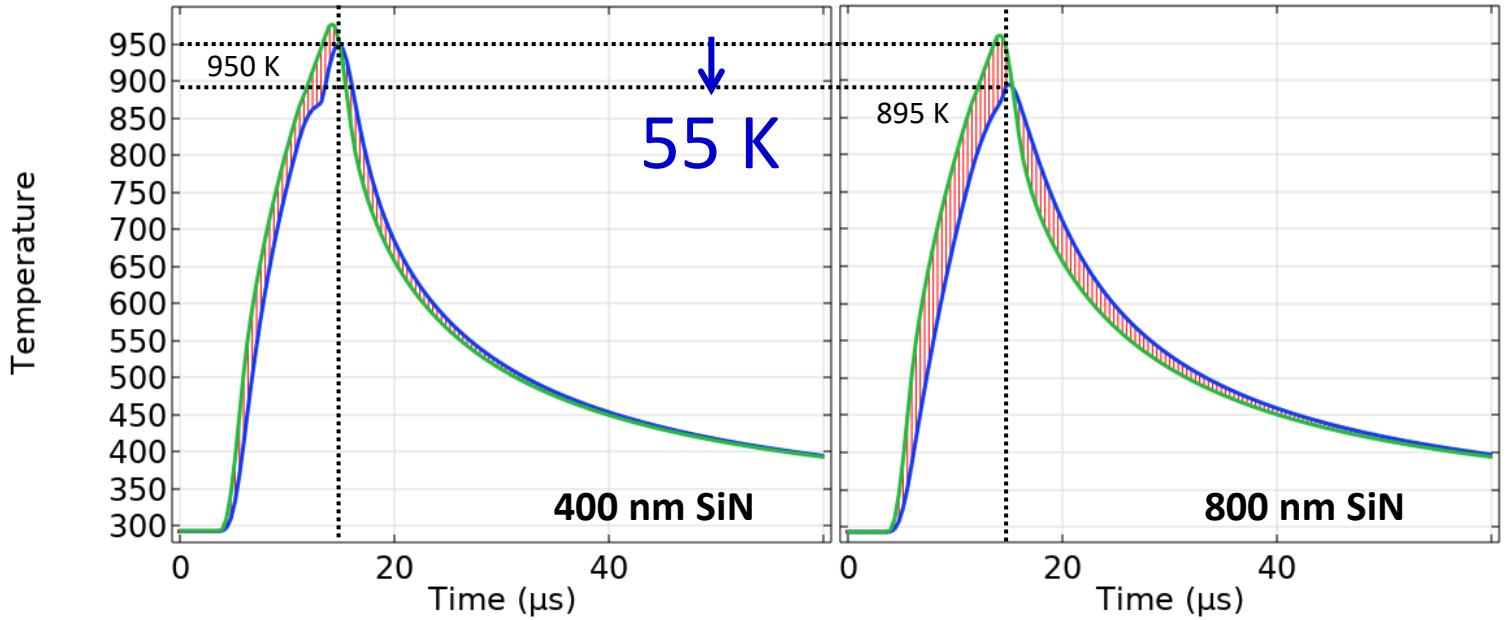
Durability and source of failure



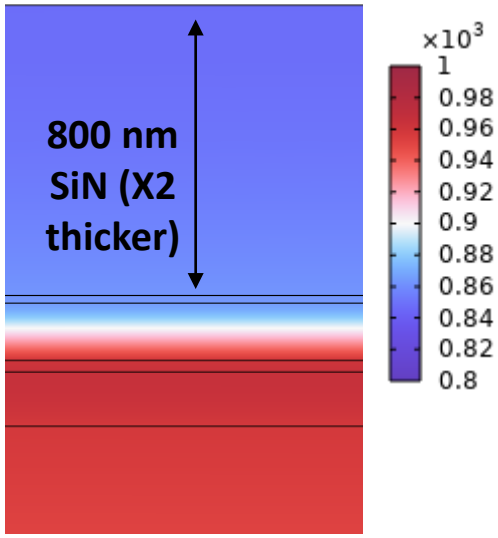


Thicker SiN_x layer leads to less temp. rise – leads to less thermal stress in the encapsulating layer



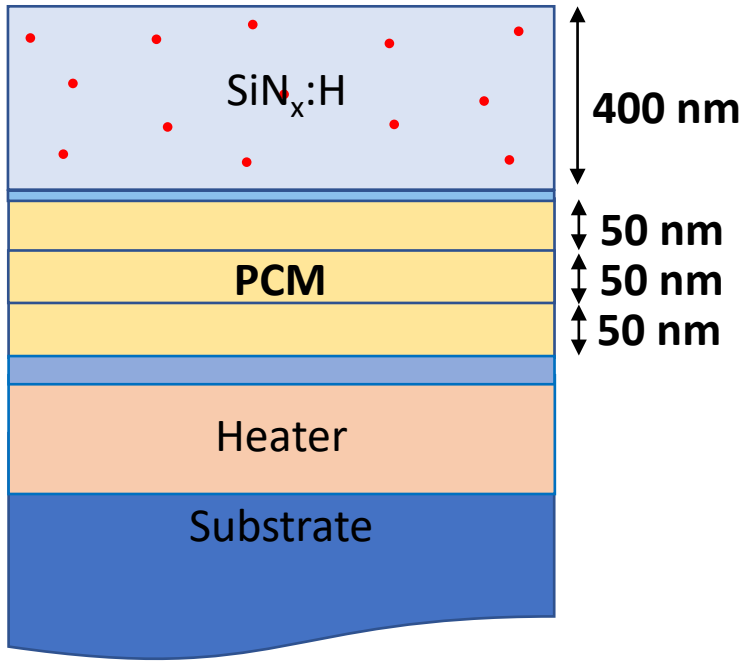


SiN_x Stays cooler



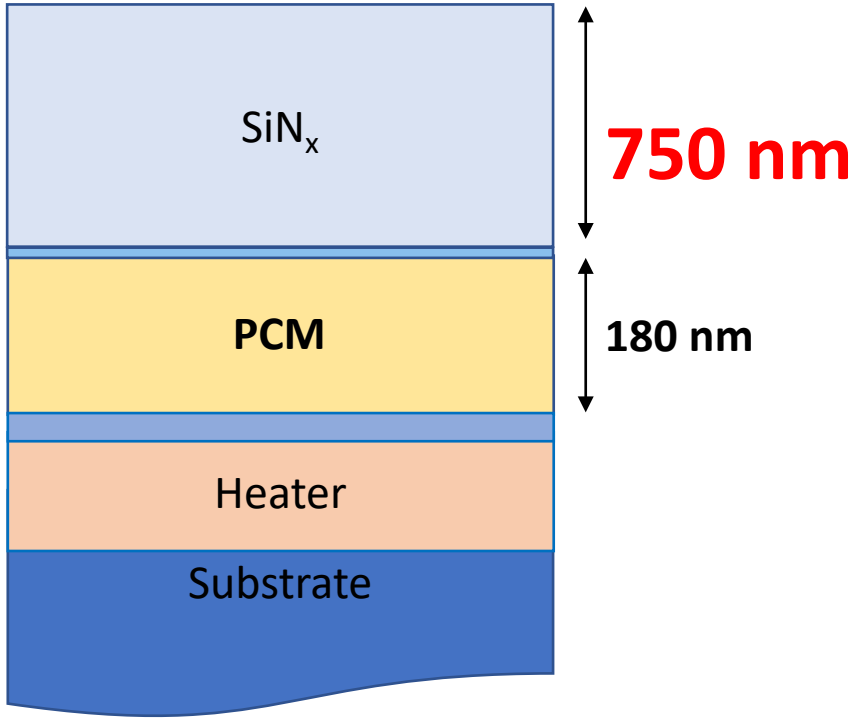
Improving the device performance

Batch - 01



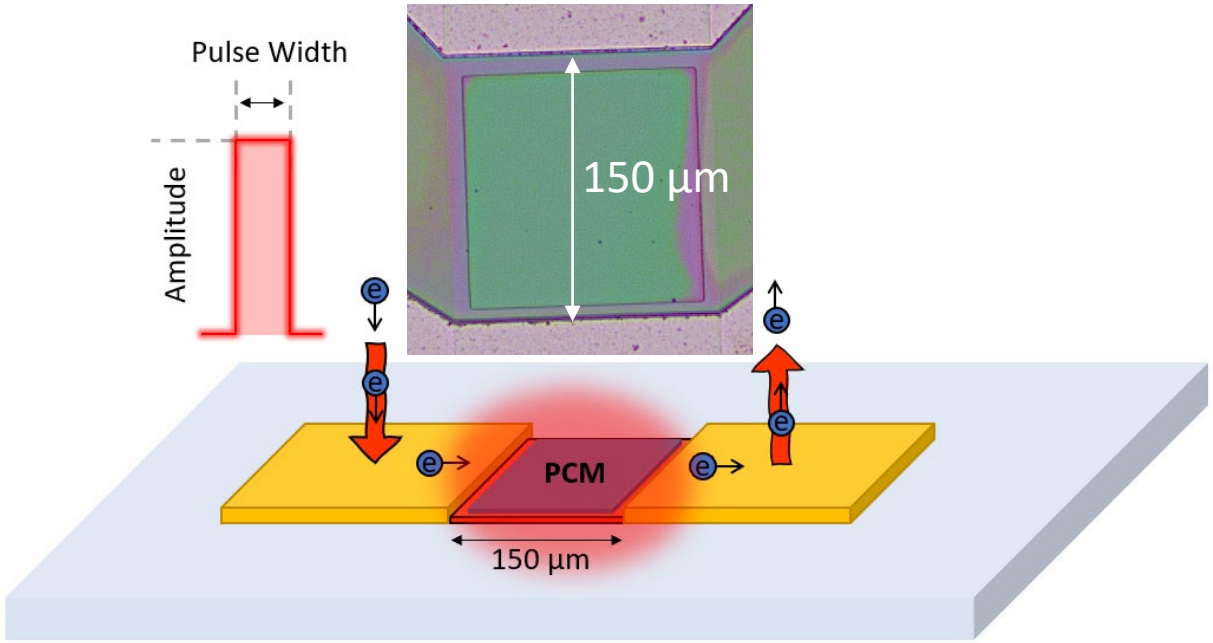
- SiN_x → PECVD (prone to hydrogen contamination, lead to degradation of mechanical properties
- SiN_x → with H content
- SiN_x → ~400 nm
- PCM → 3 deposition
- Al_2O_3 → 110 °C

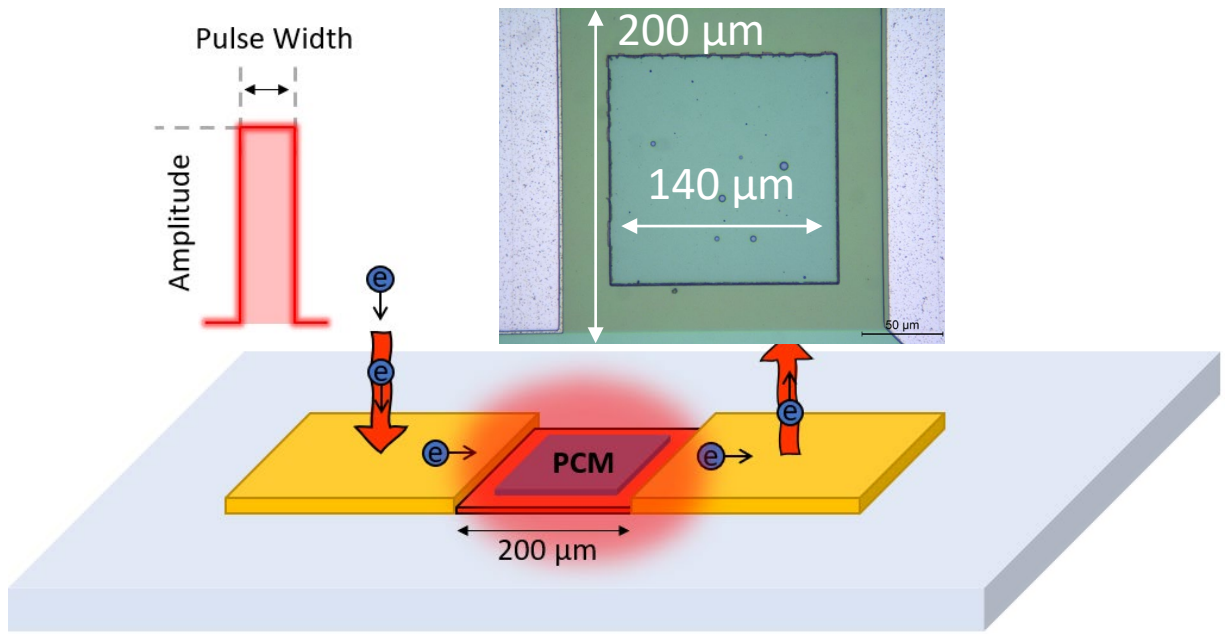
Batch - 02

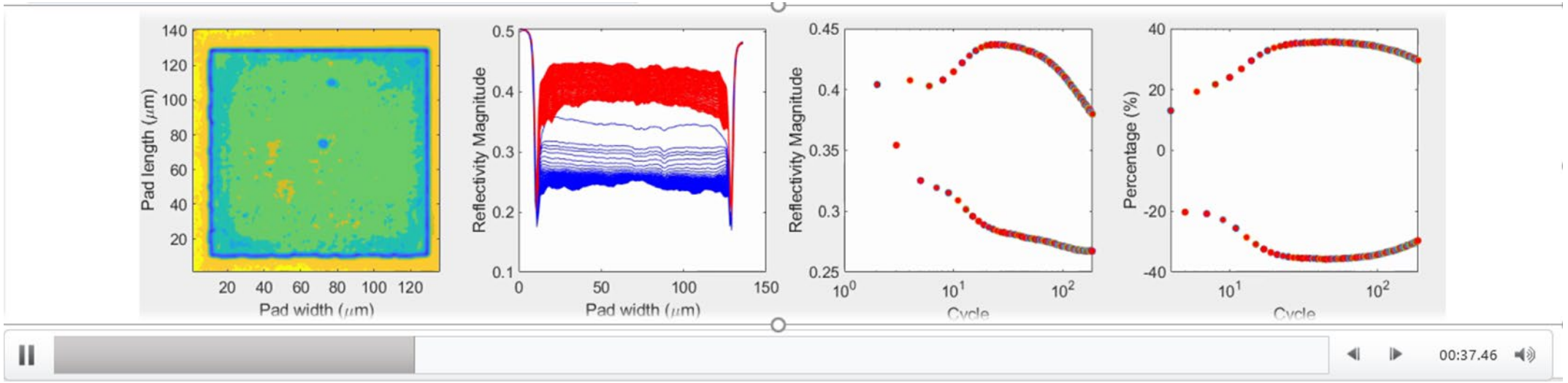


- SiN_x → Sputtered
- SiN_x → without H content (No H-terminated bonds & formation of nano-porosity in film)
- SiN_x → ~750 nm
- PCM → 1 deposition
- Al_2O_3 → 250 °C

Improving the device endurance

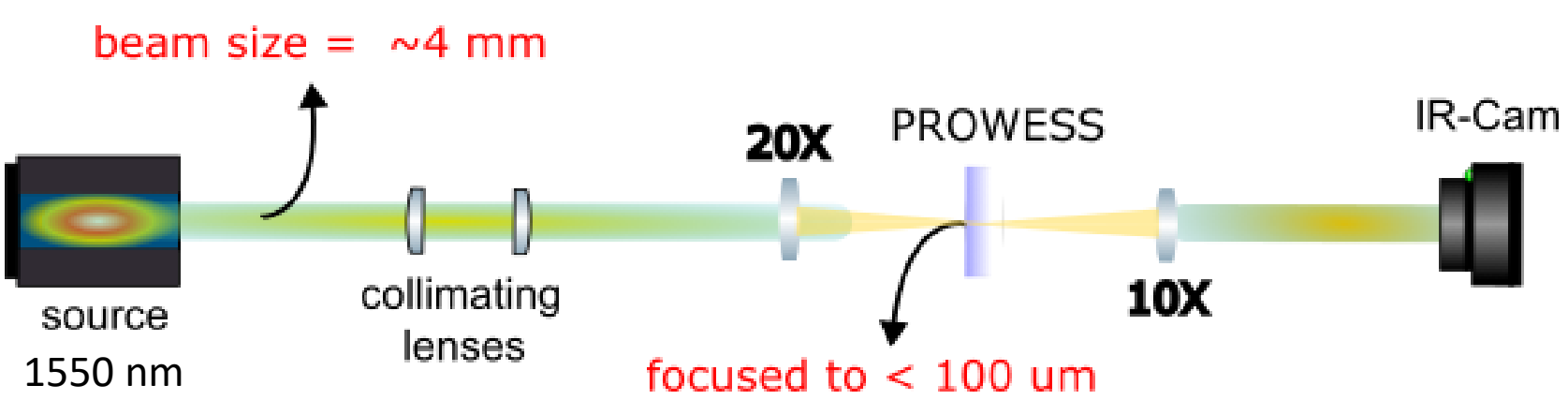


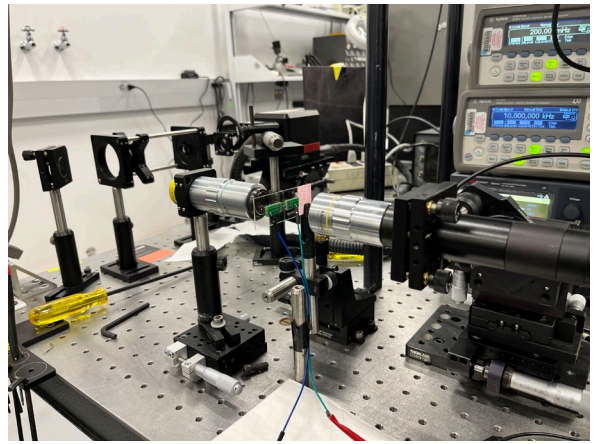




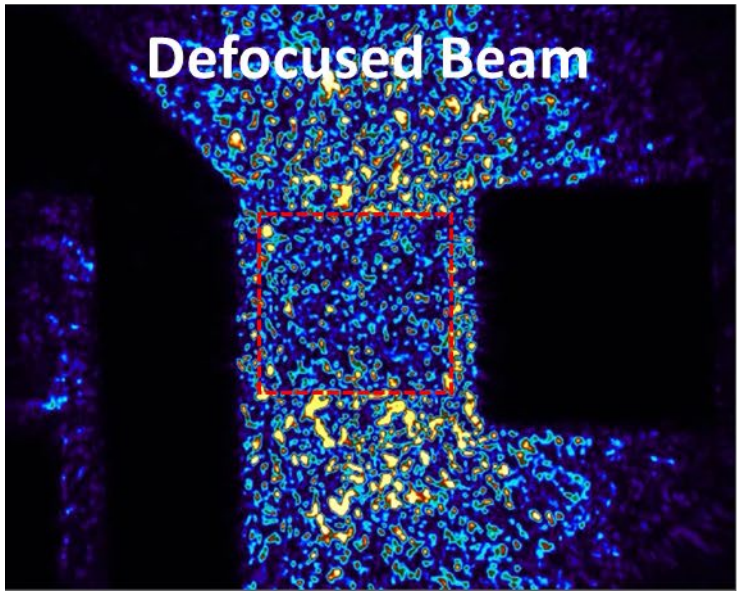
K. Aryana. et al, Scaling up phase change material based devices (under review, 2023)

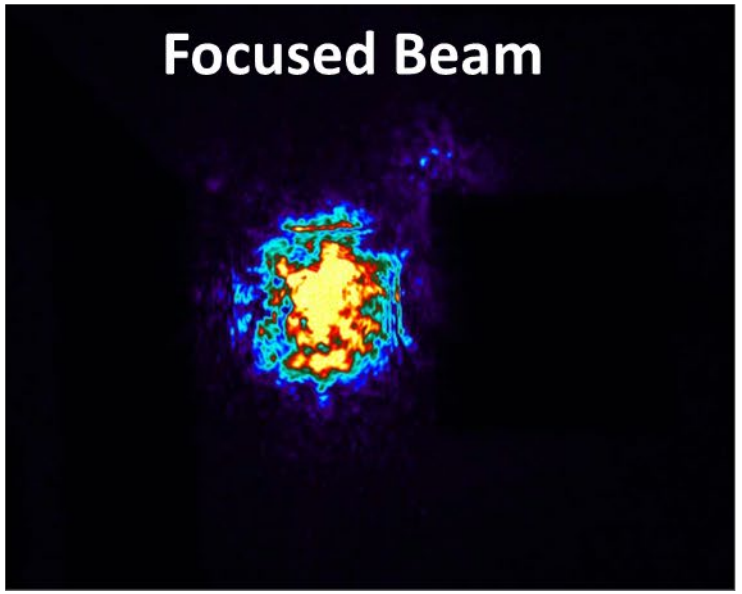
Light manipulation – No surface functionality

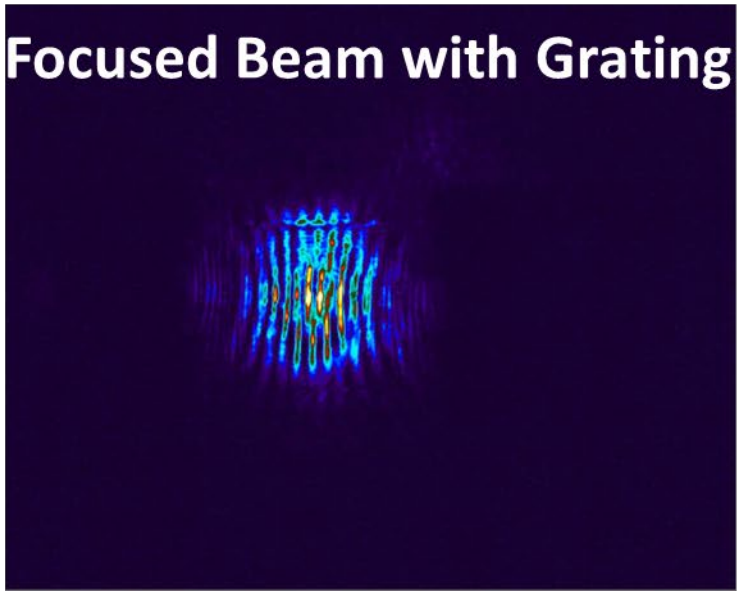




Investigate how the PCM behave across phase transition when a monochromatic 1550nm beam is focused on the PCM pixels



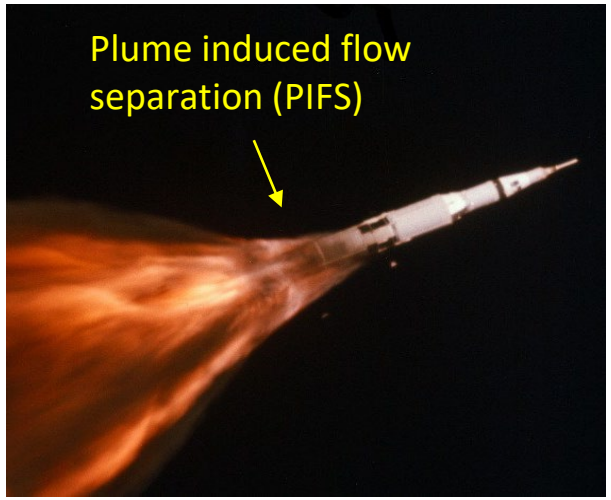




P-ACTIVE at NASA

NASA Scientifically Calibrated In-Flight Imagery

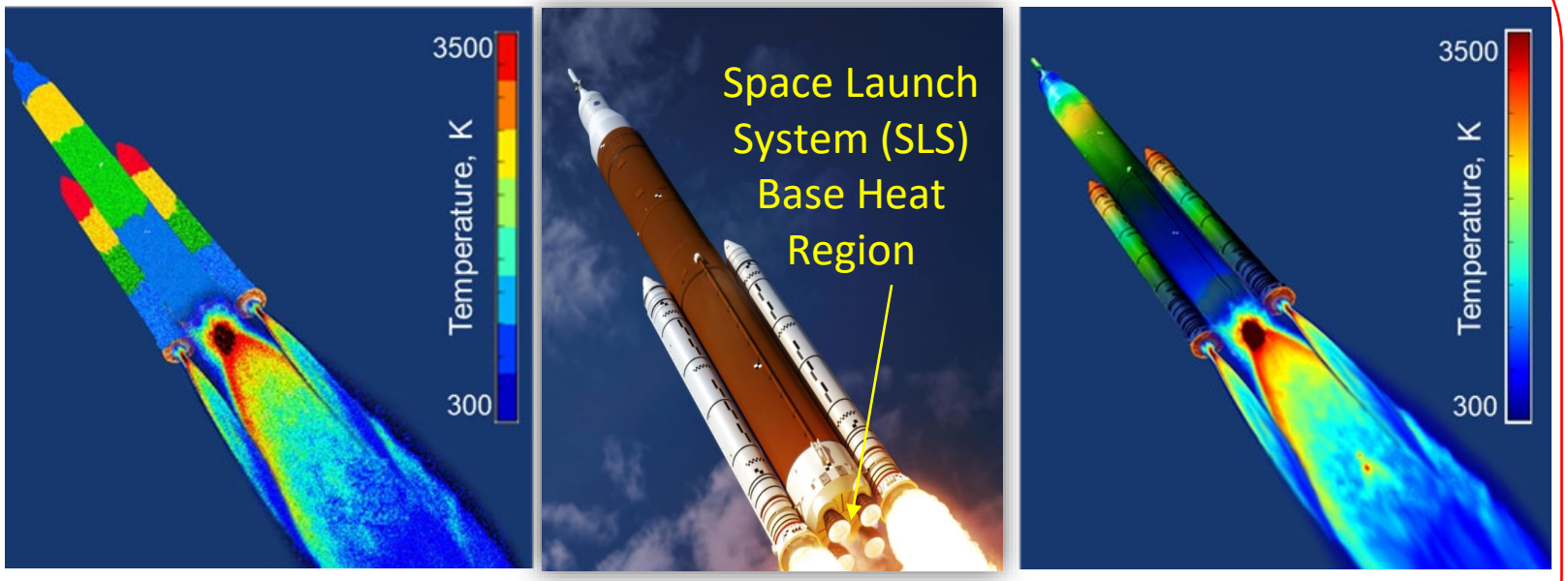
Apollo Saturn V



Kerosene + LOX

- Plume in VIS spectrum
- No temperature data

Artemis-1 Program



Hydrogen + LOX = H2O

- Plume in MWIR spectrum
- Temperature retrieval possible

Goal: Obtain high quality thermal imagery data of the SLS base heat region and PIFS during a ascent to validate / reduce required TPS mass for future flights – increased payload

Need: Reliable and adaptable MWIR filter for increased temperature accuracy from the current high speed (MHz), narrow band filter wheel – for next-generation active thermal imaging monitoring for future missions.

Credit: scifli.larc.nasa.gov

P-ACTIVE for **SCIFLI Airborne Multispectral Imager (SAMI)**

Extra information

Temporal

Spectral resolution

Accuracy improvement

Independent emissivity

NASA tech (US patent)

Image detail improvement

Dynamic range improvement

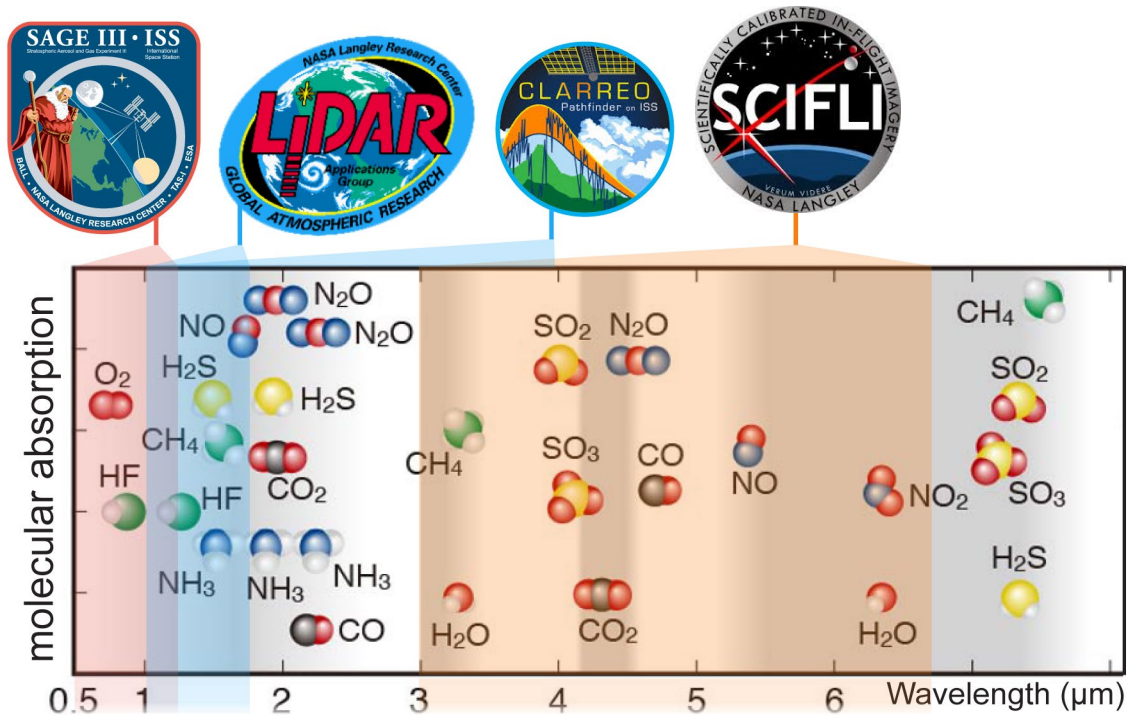
New aircraft opportunity

Smaller space

SWaP-C benefits

Filter wheel		P-ACTIVE filter
800g	**Weight**	10g
725cm^3	**Volume**	0.253cm^3
15W to power motor	**Power**	~mW average power to tune filter
10s of milliseconds (< kHz imaging)	**Temporal resolution (Speed)**	10s of nanoseconds (GHz imaging)
~4-5 wavelength points	**Spectral resolution (Accuracy)**	~10-20 wavelength points

1-10 µm waveband, “Spectral Fingerprint”



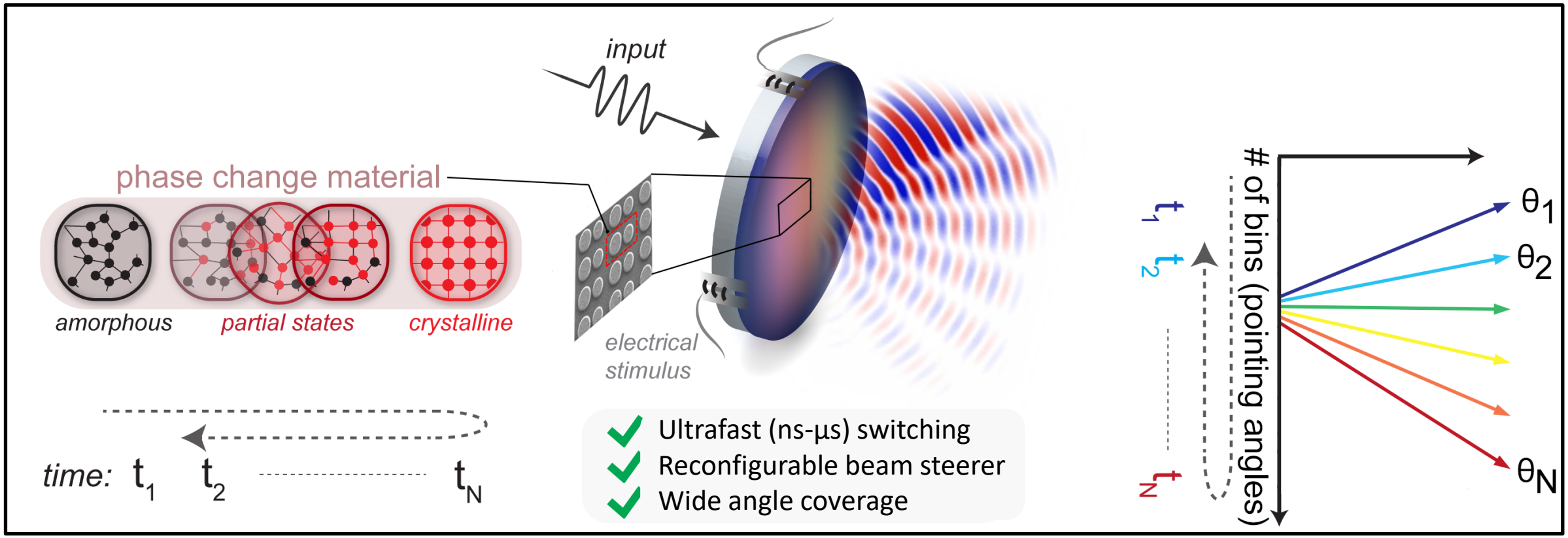
- **Chemical/Gas sensing** – LIDAR Science mission
  - Rapid profiling of targeted observables, greenhouse gases (NO_2, CO_2, CO, SO_2), ozone, water vapor
  - DIAL (Differential Absorption Lidar) **on/off switch**: Capability to measure H_2O vapor & CH_4 profiles for deeper understanding of clouds responding to warming climate from greenhouse gases
  - SAGE III / IV mission **multi-spectral filter** wheel
  - (future) SAGE-IR in space (SmallSat-based)

Thermal imaging – SLS Space mission
- Dynamic targets (e.g., turbulent plumes, volcano gases)
- SCIFLI project **multi-spectral filter** wheel: H_2O & CO_2/CO rocket plume emission
- Thermal Imaging Diagnostic for Satellite Thrusters

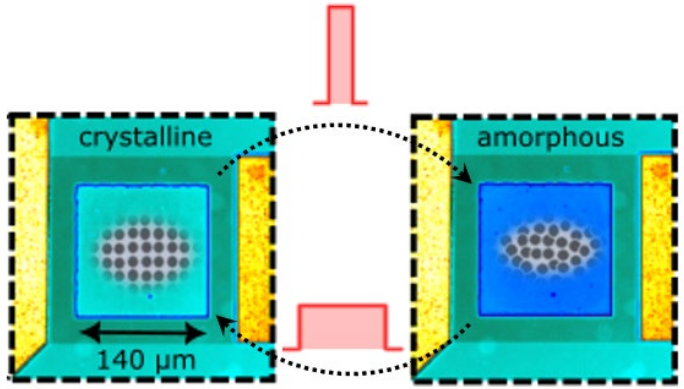
Beyond the P-ACTIVE

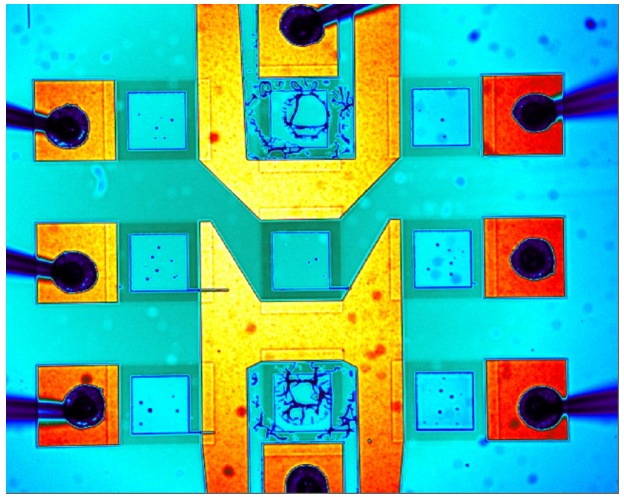
Beam steerer using PCM metasurface

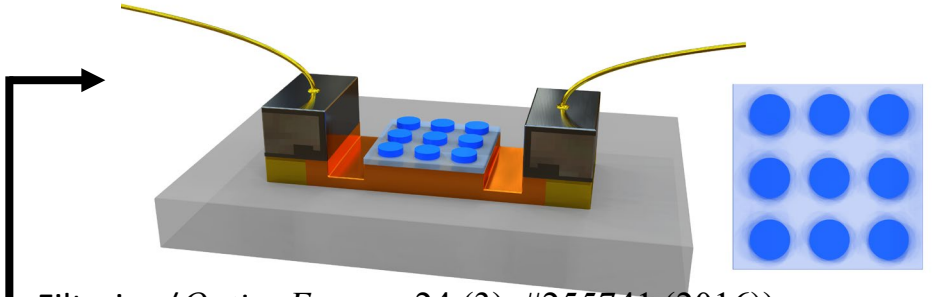
✓ manipulates light via spatially-arranged sub-wavelength nanostructures made from PCMs active wavefront control by tailoring the phase of each constituent nanostructure



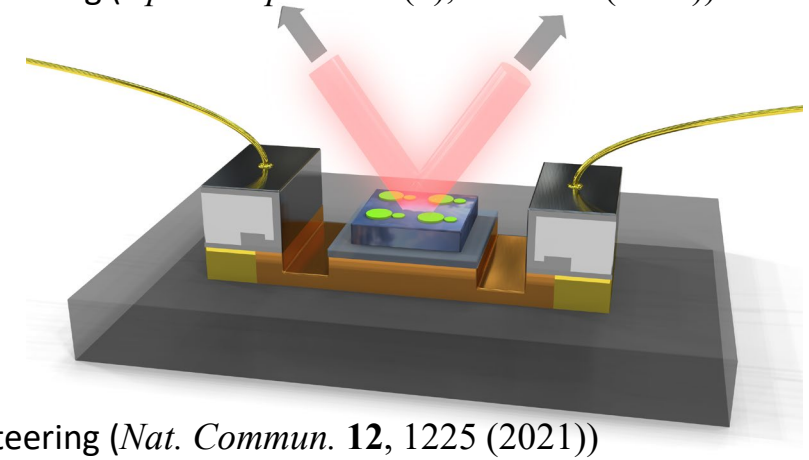
Reconfigurable Metasurface Optics based on PCM



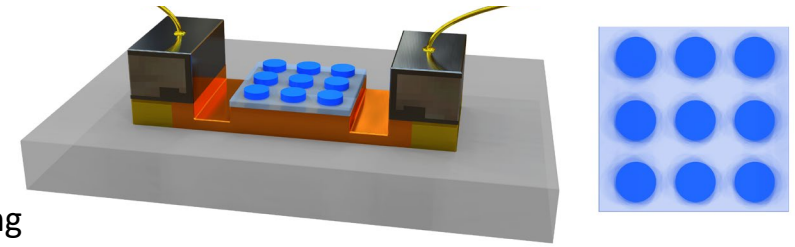




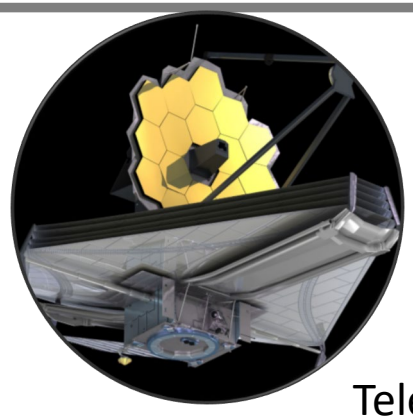
Filtering (*Optics Express* 24 (3), #255741 (2016))



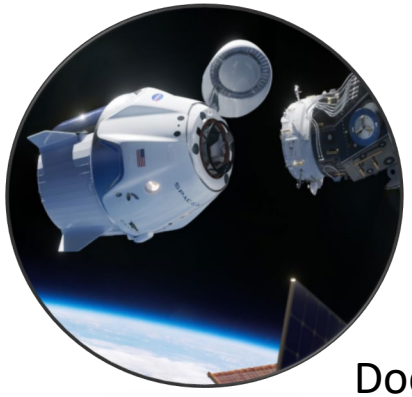
Steering (*Nat. Commun.* **12**, 1225 (2021))



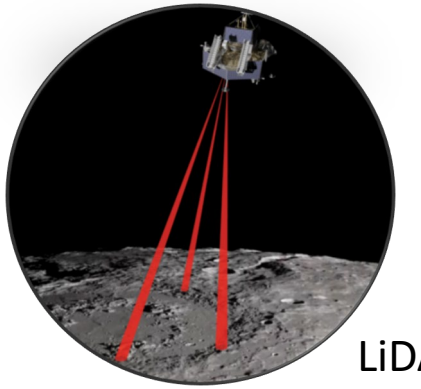
Focusing



Telescope



Docking



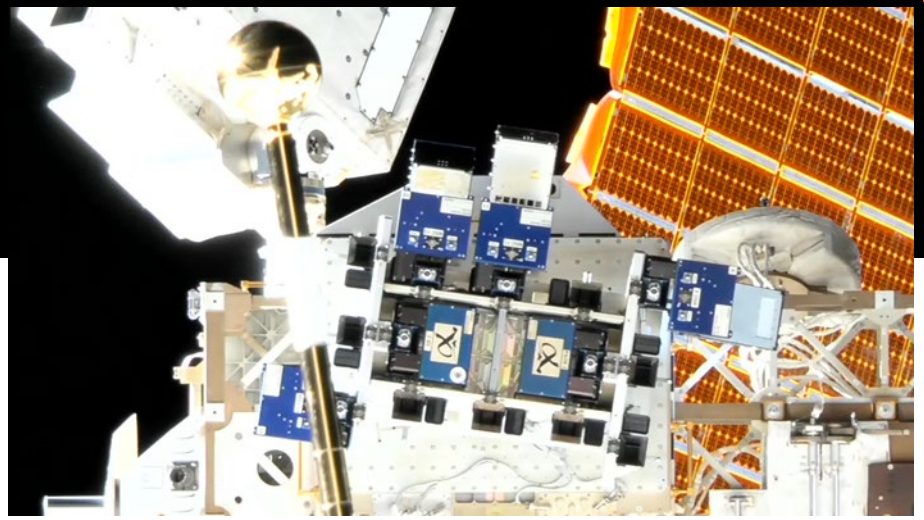
LiDAR

Path forward to Space

PCM in ISS through MISSE-14 test campaign

- MISSE - Materials International Space Station Experiment – materials and devices exposed to the space environment (LEO, space below an altitude of 2,000 km), atomic oxygen, -120 °C to 120 °C temperature extremes, hard vacuum, UV radiation, charged-particle radiation.

Launch 02/20/2021	Unpack / unsealing 04/08/2021	Deployment on orbit 04/25/2021		Return 01/25/2022
• Preparation • Preflight characterization			Exposure & monitoring 06/21/2021-12/6/2021 (148 days 21 hours 11 minutes)	• Retrieval • Post flight characterization



H. J. Kim et al, Nature Materials (under review, 2023)

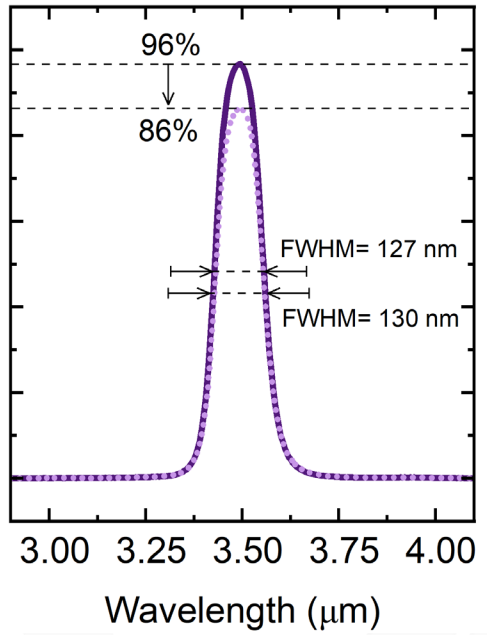
MISSE results

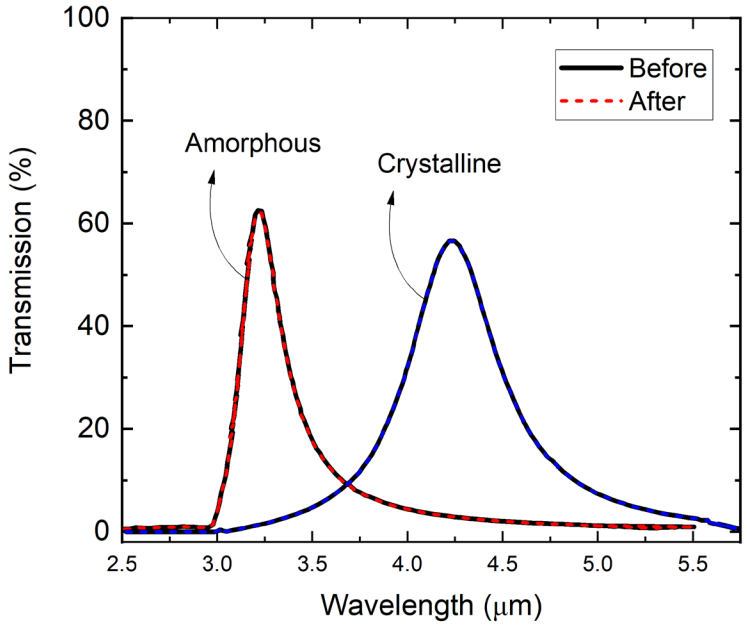
- Different chalcogenide-based PCM (GST, GSST, SbS) are sent to ISS for exposure to LEO environment.

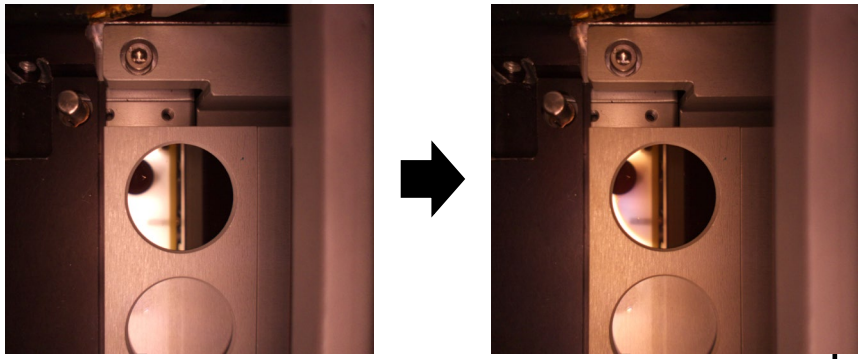
- Relatively extreme environment is recorded for the 6-month period that the specimens were in space:
  - ✓ **Nearly 75 °C temperature fluctuations**
  - ✓ **100X higher Radiation**
  - ✓ **300X higher UV exposure**

- Visual variation is observed in a few specimens after return to earth, mostly those exposed to Zenith orientation.

- Transmission of F-P filters is reduced by 5 to 10% but no change of the PNA filters (with SiO_2 capping layer).

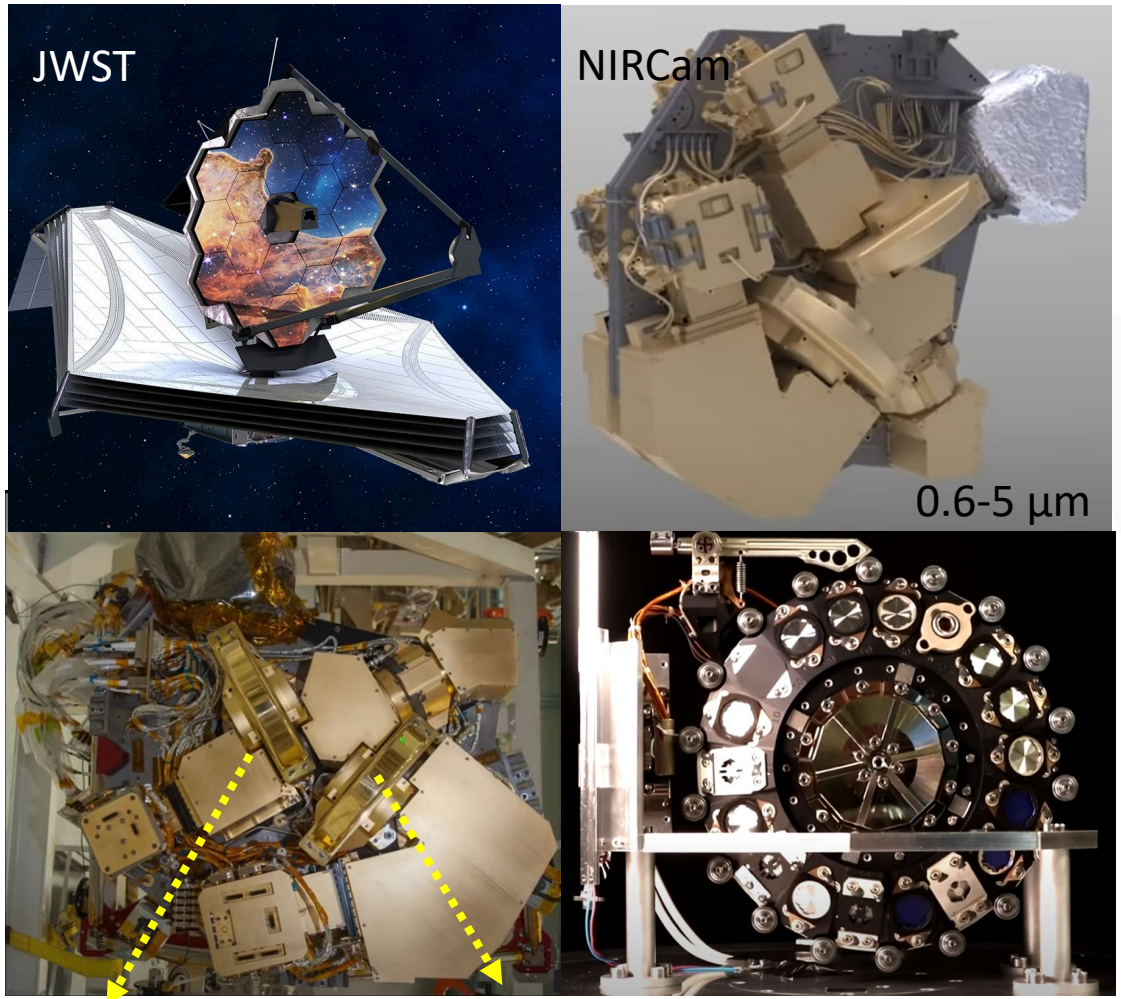






National Aeronautics and Space Administration

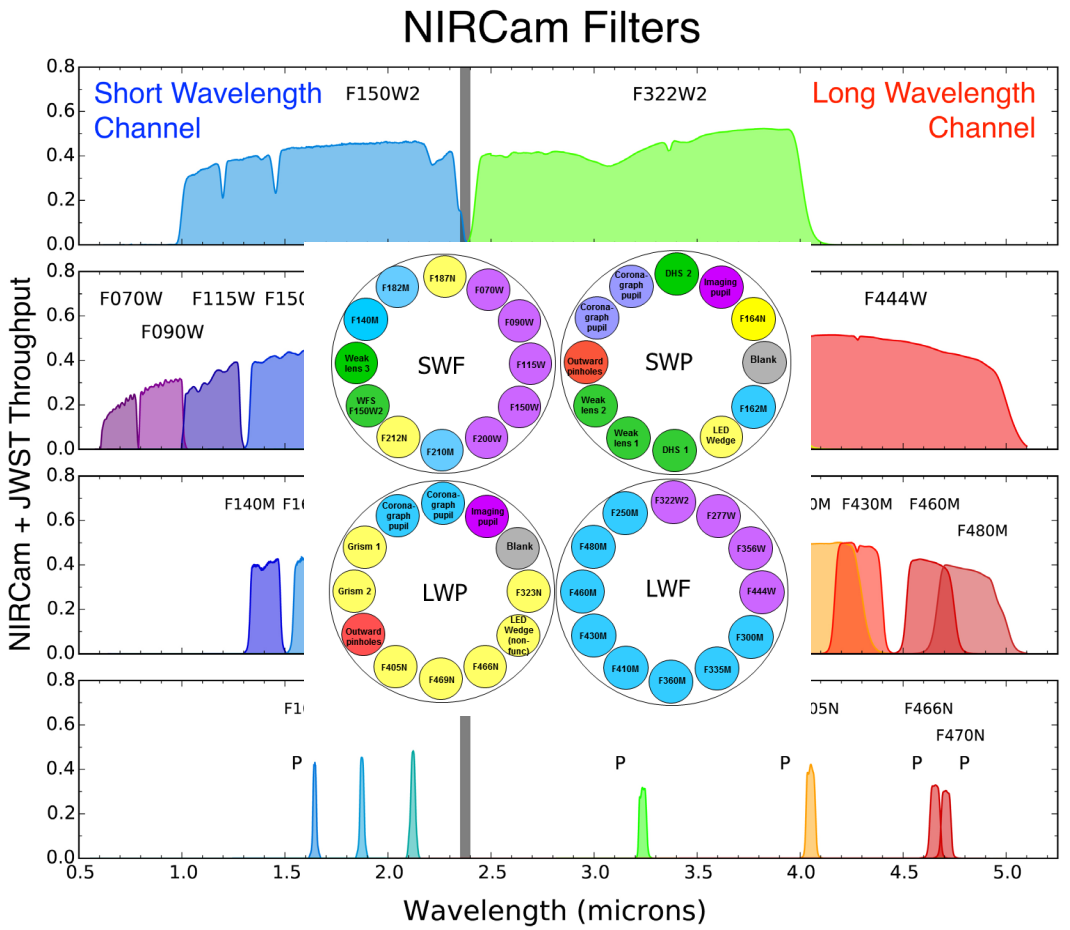
P-ACTIVE for Space Explorations



https://www.youtube.com/watch?v=MzWfUK0yvdY

Long Wavelength Filter Wheel

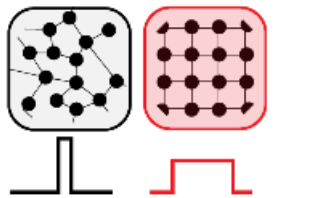
Short Wavelength Filter Wheel



National Aeronautics and Space Administration

Summary

a **Materials Property** → **b** **Technology /Sub-system** → **c** **Applications**



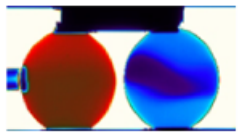
Refractive Index
$\Delta n, \Delta k$
Resitivity
$\Delta \rho$

Joule heating

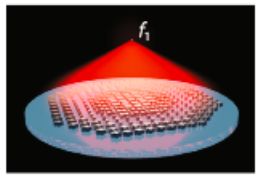
Optical pulse
Electrical stimuli

I/O

Tunable optical filters
- Smart coatings
- Switchable color pixels

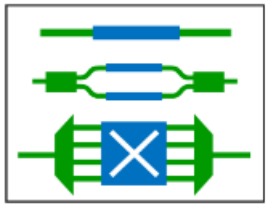


Active metaoptics
- Beam steering
- Flat tunable lenses



Switchable Fibre-optics

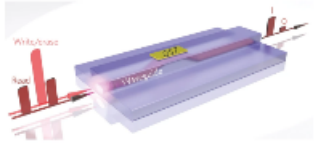
Photonic integrated circuits
- Optical phase modulator
- Optical ampltiude modulator



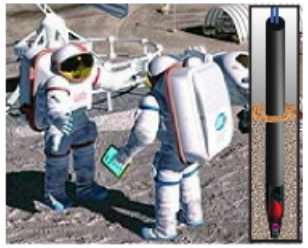
Miniaturized spectrometers

Multifunctional biosensors

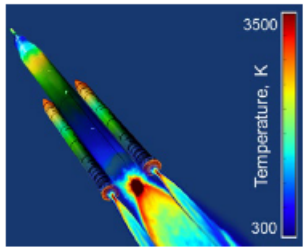
Non-volatile memory
- Reconfigurable data elements



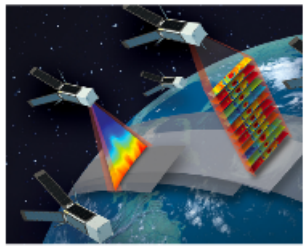
Local Optical Diagnostics
- Lab-on-a-Chip
- Astronaut Health Monitoring
- Optical gyroscopes
- Thermal control / visualization



Remote sensing
- LIDAR
- Wide-waveband thermal imaging
- Combustion diagnostics
- Hyperspectral imaging
- Miniaturized optical assemblies



Optical Communications
- High speed free-space & datacomms
- Inter- and intra-satellite links



Displays and panel coatings

Photonic Computing
- Low power data storage
- Quantum & neuromorphic circuits

T. Gu et al, Nature Photonics, https:// doi.org/10.1038/s41566-022-01099-4 (2023)

NASA LaRC Team

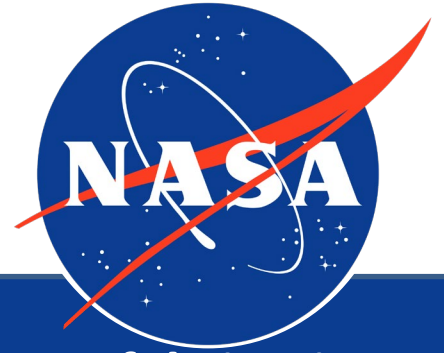
- Dr. Kiumars Aryana
- Mr. Scott Bartram
- Mr. Stephen Borg
- Mr. William Humphreys
- Dr. Aram Gragossian
- Dr. Nathan Dostart
- Mr. Tim Berkoff
- Mr. David Macdonnell

MIT Team

- Prof. Juejun Hu
- Mr. Cosmin-Constantin Popescu
- Dr. Tian Gu

MIT LL

- Dr. Steven Vitale



Thermal modeling /fabrication characterization/ applications

PCM & metasurface optics

Heater fabrication

I want to join at NASA!

NASA Internships Program

- Deadline for Spring applications is Nov. 11.
- NASA is accepting applications for Summer '23 internships. More projects are being added weekly.
- Summer application deadline is Mar. 10. Summer session begins June 5
- NASA interns typically work during the hours of 8 a.m. to 5 p.m., Monday - Friday, unless otherwise stated

Good for gaining knowledge and creating contacts

NASA Pathways Program

https://www.USAJobs.gov

- Opportunities Advertised at https://www.USAJobs.gov
- No set schedule of opportunities. It is need based.
- Pathways interns typically work at a NASA center during the Summer and return to school in Fall.
- After graduation, Pathways Interns may be hired by NASA as Civil Servant (depending on funding and need)

Great path to become a NASA Civil Servant

NASA DEVELOP Program

HOME / WHAT WE DO / CAPACITY BUILDING

- DEVELOP HOME
- INSIDE DEVELOP
- APPLY TO DEVELOP
- PARTNER WITH DEVELOP
- DEVELOP PROJECTS
- DEVELOP FAQ

FOSTERING TODAY'S SOLUTIONS AND TOMORROW'S WORKFORCE

DEVELOP cultivates the next generation of leaders and Earth observation users. We work with communities and organizations to address environmental and policy concerns through the practical application of NASA Earth science information.

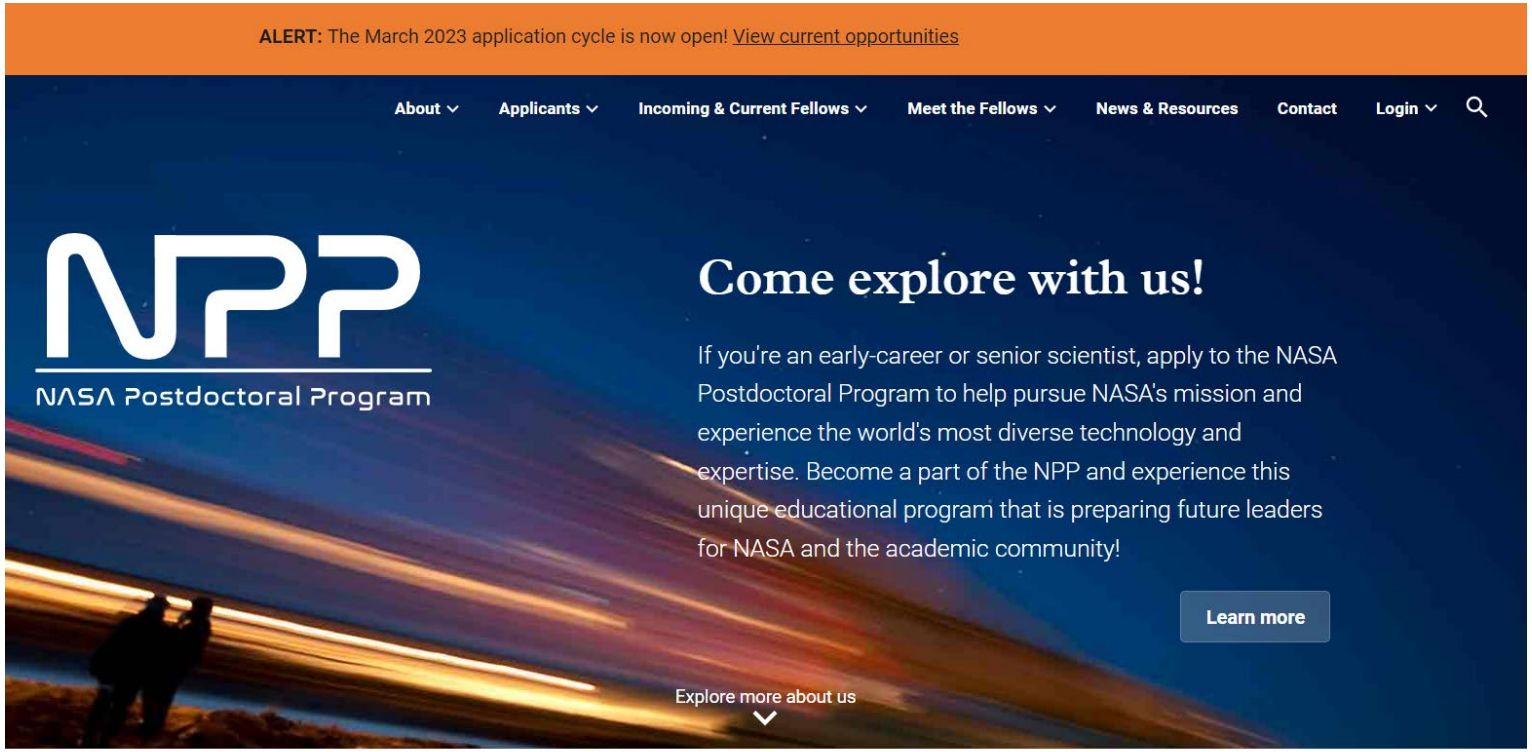
DEVELOP conducts feasibility studies that bridge the gap between Earth science information and society. These projects help both participants and partners learn more about using geospatial information. Projects address priorities and concerns in nine thematic areas: Agriculture, Climate, Disasters, Ecological Forecasting, Energy, Health & Air Quality, Urban Development, Water Resources, and Wildfires.

TERM & DATES	APPLICATION WINDOW	RECOMMENDATIONS DUE	NOTIFICATION TIMELINE
Spring 2023 (Term Dates: Jan 23 - Mar 31)	Aug 29 - Oct 7, 2022	Oct 21, 2022	Dec 2022 - Jan 2023
Summer 2023 (Term Dates: Jun 5 - Aug 11)	Jan 16 - Feb 24, 2023	Mar 10, 2023	Apr-May 2023
Fall 2023 (Term Dates: Sep 11 - Nov 17)	May 15 - Jun 23, 2023	Jun 7, 2023	Aug 2023

- Three Sessions per year
- Earth Science Applications for regional climate challenges.

Good for gaining knowledge about application of earth science data products

NASA Postdoctoral Program



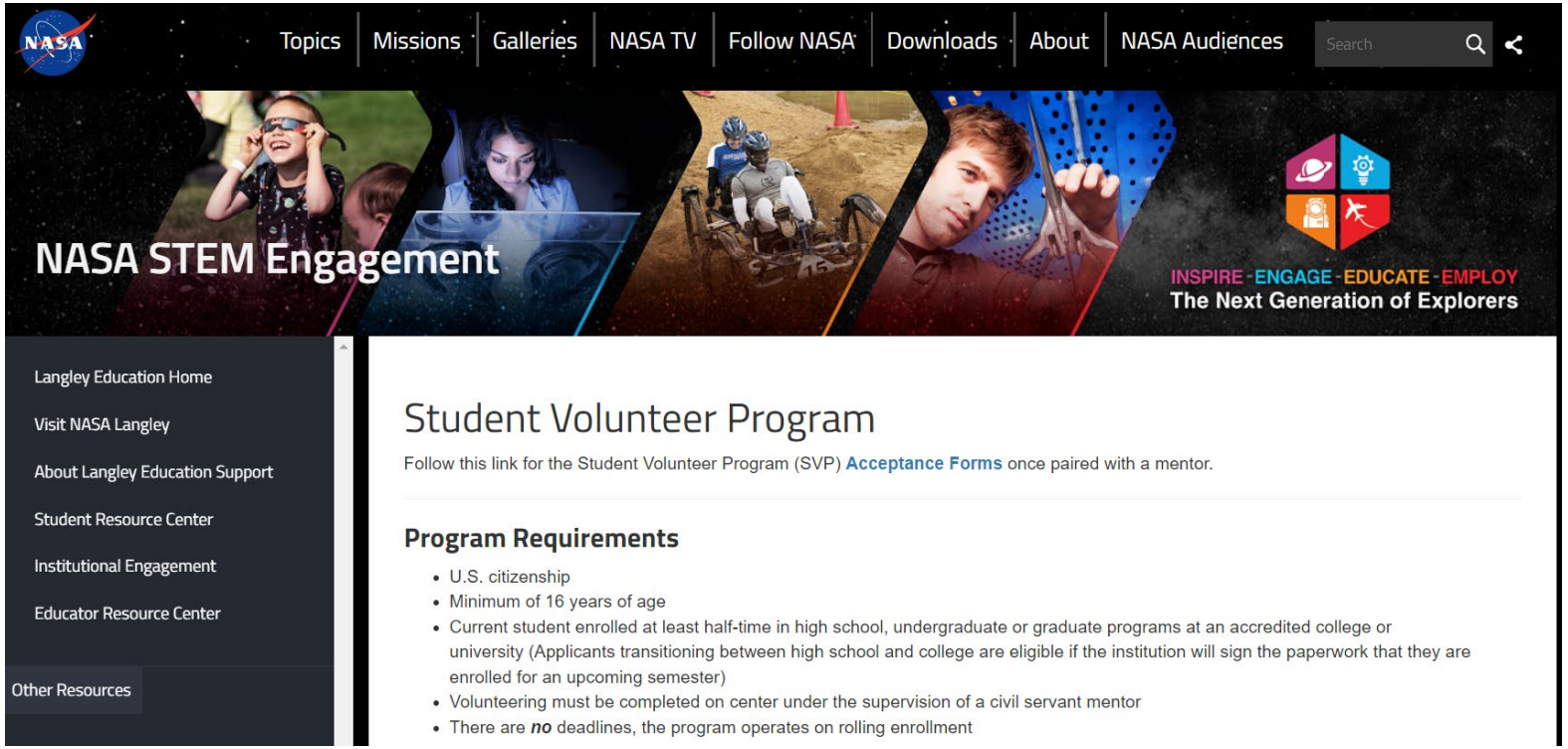
Welcome to the NPP Gateway! Find a Fellowship

- Multiple Application Windows per year
- Opportunities span Science and Technology.
- Applicant proposals are scored then selected.

NPP work on their research while gaining NASA contacts and experience

NASA Student Volunteer Program

- No Deadline
- On-Center work required
- Mentor needed
- Not a paid internship



https://www.nasa.gov/langley/education/volunteer

Good for gaining knowledge and creating contacts

NASA's Top Contractors for FY20

VENDOR NAME AND WEBSITE		TOTAL DOLLARS
California Institute of Technology (JPL)	https://acquisitions.jpl.nasa.gov	$2,814,488,510
The Boeing Company	http://www.boeingsuppliers.com/esd/getstart.html	$1,484,105,650
Lockheed Martin Corp.	https://www.lockheedmartin.com/en-us/suppliers.html	$1,397,590,743
Northrop Grumman	https://www.northropgrumman.com/suppliers	$1,359,827,527
Jacobs Technology, Inc.	https://www.jacobs.com/client-advocate#Suppliers	$1,060,566,999
Space Exploration Technologies Corp.	https://www.spacex.com	$847,990,951
KBR, Inc. (includes Wyle & SGT)	https://kbr.com/en/contact-us	$650,213,921
Aerojet Rocketdyne, Inc.	https://www.rocket.com/suppliernet	$502,554,463
Science Applications International Corporation (SAIC)	https://www.saic.com/suppliers	$495,196,146
Leidos (includes Dynetics)	https://www.leidos.com/suppliers	$401,101,998
Sierra Nevada Corporation	https://www.sncorp.com/suppliers	$344,728,532
United Launch Services, LLC	http://www.ulalaunch.com	$275,796,019
Science Systems and Applications, Inc. (SSAI)	https://www.ssaihq.com	$272,773,396
Johns Hopkins University	https://hopkinsmedicine.org/business/index.html	$257,391,750
ASRC Federal, Inc.	https://asrcfederal.com/contract-vehicles#	$256,159,525
Blue Origin Federation, LLC	https://www.blueorigin.com/fly-with-us/become-a-supplier	$230,164,399
Syncom Space Services, LLC	http://www.syncomspaceservices.com/vendors.aspx	$197,354,994
Peraton, Inc.	https://www.peraton.com/supplier-diversity	$156,048,832
Maxar (includes Space Systems Loral)	https://www.maxar.com/legal/suppliers	$154,882,785
Raytheon Company	https://www.rtx.com/suppliers	$144,183,569
	TOTAL	$13,303,120,710

- Contractors Provide Critical Services
- Companies offer flexible hiring practices and comparable benefits
- Research Contracts and Companies

NASA Contractors are good places to start a career at NASA

Key Take-Aways

Opportunities for working with NASA or for NASA are available!

MSE is the core of Science and Space instruments at NASA!

Do your research & Try to engage!

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